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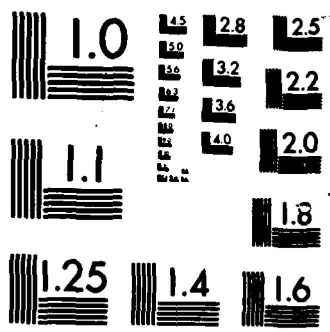

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DEEP SEA SHIP MOOR

FINAL ENGINEERING REPORT

VOLUME 5

FPO-1-78 (16)

AUGUST 1978

Ocean Engineering and Construction

86 1 28 107

[illegible] RESTRICTIVE MARKINGS

[illegible] SECURITY CLASSIFICATION [illegible]

3. DISTRIBUTION AVAILABILITY OF REP.
Approved for public release;
distribution is unlimited

[illegible] DECLASSIFICATION [illegible] SCHEDULE

[illegible] PERFORMING ORGANI[illegible]

5. MONITORING ORGANIZATION REPORT #

[illegible] NAME OF PERFORM[illegible]
[illegible]ctronic Syst[illegible]
[illegible]eral Electric Comp[illegible]

7a. NAME OF MONITORING ORGANIZATION
Ocean Engineering
& Construction
Project Office
CHESNAVFACENGCOM

[illegible]. ADDRESS (City, State, and Zip Code)
[illegible]racuse, N.Y.

7b. ADDRESS (City, State, and Zip)
BLDG. 212, Washington Navy Yard
Washington, D.C. 20374-2121

[illegible]. NAME OF FUNDING ORG. [illegible] SYM

9. PROCUREMENT INSTRUMENT INDENT #

[illegible]. ADDRESS (City, State, Zip)

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT #	PROJECT #	TASK #	WORK UNIT ACCESS #

11. TITLE (Including Security Classification)
[illegible]p Sea Ship Moor User's Manual DESMOOR

12. PERSONAL AUTHOR(S)
[illegible]. Webster

13a. TYPE OF REPORT
13b. TIME COVERED FROM [illegible] TO
14. DATE OF REP. (YYMMDD) 76-08
15. PAGES 5 vol.

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if nec.)
Mooring systems, DESMOOR

19. ABSTRACT (Continue on reverse if necessary & identify by block number)
This report documents the DESMOOR computer program which selects trial designs of mooring systems for surface ships in deep water. Either slack (negatively buoyant catenary) or taut (neutrally buoyant) moors can be treated. Given design coefficients for the mooring line material, the number and (Con't)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
UNCLASS/UNLIMITED [illegible] DTIC

21. ABSTRACT SECURITY CLASSIFICATION

22a. NAME OF RESPONSIBLE INDIVIDUAL
Jacqueline [illegible]

22b. TELEPHONE
202-433-3881

22c. OFFICE SYMBOL

DD FORM 1473, [illegible]

SECURITY CLASSIFICATION OF THIS PAGE

[illegible] design constraints, the [illegible] In the case of slack moors [illegible] search is then made of defined [illegible] and hawsers as [illegible] program utilized the equations of [illegible] on the ship and the ship is presumed [illegible] and [illegible] The external loadings on [illegible] wind and current load tables or [illegible] scaling is used when the load [illegible] to approximate the loads on another. [illegible] preliminary design tool to be used in [illegible] junction [illegible] ing static and dynamic analysis [illegible]

DSSM-5

FINAL ENGINEERING REPORT

DEEP SEA SHIP MOOR
COMPUTER SIMULATION PROGRAM

Contract Number N62477-76-C-0002

by

R. L. WEBSTER

DECEMBER 30, 1976
REVISED JULY 1978
REVISED SEPT 1978

PREPARED FOR

OCEAN ENGINEERING AND CONSTRUCTION PROJECT OFFICE
CHESAPEAKE DIVISION
NAVAL FACILITIES ENGINEERING COMMAND
WASHINGTON, DC

by

ELECTRONIC SYSTEMS DIVISION
GENERAL ELECTRIC COMPANY
SYRACUSE, NY

Revised JULY 1978

Revised SEPT 1978

ERRATA

The July 1978 revision to this document has changes on the pages listed below:

iii
1
9
17
18
31
225 through end of Addendum I.

The September 1978 revision to this document has changes on the pages listed below:

54

Revised JULY 1978

Revised SEPT 1978

ABSTRACT

This report summarizes the effort to implement computer-aided design and analysis procedures for deep sea ship moors. Two computer programs were developed: the DESMOOR program, which generates trial mooring designs, and the SEADYN/DSSM, which is an integration of a general purpose finite element program for cable analysis with the ship mooring analysis. The planning and performance on the contract are reviewed and a critical discussion of the effort is given. Areas for further development are identified. Appendices contain the Statement of Work and nine Letter Reports describing the progress of the effort.

ADMINISTRATION INFORMATION

This report is submitted in compliance with Item No. (12) of the Milestones and Deliverables Schedule of Contract N62477-76-0002 dated 17 June 1975 as revised 4 August 1975.

CONTENTS

Revised JULY 1978

1.0 INTRODUCTION

This report summarizes the effort to implement a computer-aided design and analysis capability applicable to the Deep Sea Ship Mooring (DSSM) problem. The project spanned a period of more than a year and resulted in the development of one entirely new computer program (DESMOOR), an extensive revision and extension of an existing computer program (SEADYN/DSSM), and the generation of a considerable number of reports. This effort also required an interfacing with a parallel effort on ship motion computations conducted at the David Taylor Naval Ship Research and Development Center in Bethesda, MD.

The effort was primarily one of computer program development, checkout and documentation. Although a certain amount of analytical development was required, an attempt was made to hold it to a minimum and use existing technology and solution procedures. The primary reference in this activity was the Naval Facilities Engineering Command Design Manual 26 [1]. Supporting information was obtained from the various sources listed in the Bibliography at the end of this report.

A major factor in the execution of this effort was the work reported in Reference 2. Without that as the starting point, it would have been very difficult to achieve the stated objectives.

This report deals with the planning and execution of the contracted effort. The work accomplished and the difficulties encountered are briefly discussed. Finally, recommendations for further effort are given. The Statement of Work and the various Letter Reports covering the progress of this effort are included as Appendices.

An addendum to this report is provided which describes the program debug and verification efforts which were conducted subsequent to the original submittal of the project deliverables.

2.0 CONCLUSIONS AND RECOMMENDATIONS

This effort has met all of the major objectives as set forth in the Statement of Work. Both design and analytical capabilities have been provided for dealing with the Deep Sea Ship Moor problem. A fully integrated and general static and dynamic analysis capability has been provided in the SEADYN/DSSM computer program. In fact, the program has capability beyond that anticipated. Besides providing all of the essential DSSM analysis features, the program provides static and time domain analysis capability for the mooring lines which is applicable to a whole class of problems beyond the DSSM problem (towed body and array responses, underwater truss structures, etc.).

The DSSM design program (DESMOOR) provides a very powerful tool for quickly developing preliminary design data. It also has great utility in generating trial designs to be given more detailed evaluation on the SEADYN/DSSM program.

An extensive checkout activity was conducted which verified much of the capability of the developed programs. All of the major logic paths have been exercised and results have been determined to be reasonable. In spite of serious efforts to obtain it, the checkout activity falls short of a full verification, mainly due to a lack of appropriate checkout cases supported by experimental or analytical results. Some difficulties in obtaining an orderly checkout of the program were encountered because of a lack of timely availability of GFI data.

The capability embodied in the DESMOOR and SEADYN/DSSM computer programs is far beyond that available from any other known source. This effort has contributed significantly to the resources available for designing and evaluating ship's moors and many other offshore systems. The various areas for further development outlined in Section 7.0 should be given careful review and a program for their orderly pursuit should be implemented. Particular emphasis should be placed on the acquisition of experimental verification.

3.0 DEVELOPMENT PLAN AND HISTORY OF PERFORMANCE

The contract activity was divided into three work packages which were further subdivided into tasks. The work packages are summarized below:

Work Package 1 - Static-Load Ship-Moor Computer Analysis Program

1. Develop capability to determine the static configuration of a ship and mooring system subjected to wind, ocean currents, and workloads.

2. Develop methods for evaluating the performance of the moor relative to specified design criteria.

3. Develop algorithms to size the major components of the mooring system in accordance with established design rules and procedures.

Work Package 2 - Dynamic-Load Ship-Moor Computer Analysis Program

1. Develop an analytical model for estimating the dynamic effects of waves on a ship-moor system and implement in a computer program. Specific treatment of the steady-state effects of the wave-induced drift forces was to be included.

2. Integrate the static and dynamic analyses into a single consistent program.

3. Document, validate and demonstrate the integrated program.

Work Package 3 - Transient Dynamic Analysis of Cable Structures

1. Package and document the existing SEADYN program.

The effort was planned to span an eleven month period. The starting date for the work was 7 October 1975. Table 3-1 lists the contract deliverables, their due dates and the dates they were submitted. The slippages apparent from the delivery dates can be attributed to various factors. Each of them are discussed below.

TABLE 3-1

DELIVERABLES SCHEDULE AND PERFORMANCE

START DATE: 7 October 1975

ITEM	DESCRIPTION	CONTRACT SCHEDULE	DUE DATE	DATE SENT
1.	Development Plan	1.0 month	7 Nov 75	6 Nov 75
2.	Static Analysis Input Trade-Off	1.5	21 Nov 75	21 Nov 75
3.	Static Analysis Math Model	2.5	22 Dec 75	19 Dec 75
4.	Static Analysis Computer Implementation	3.0	7 Jan 76	26 Feb 76
5.	Static Analysis Component Selection	3.5	21 Jan 76	8 Mar 76
6.	Dynamic Analysis Input Trade-off	7.0	7 May 76	14 May 76
7.	Dynamic Analysis Math Model	7.0	7 May 76	22 June 76
8.	DSSM Integrated Program INTERIM REPORT	9.0	7 July 76	29 Sept 76
9.	Acceptance Report	10.0	7 Aug 76	Jan 77
10.	User's Manual	11.0	7 Sept 76	17 Dec 76
11.	Program Maintenance Manual	11.0	7 Sept 76	30 Dec 76
12.	Final Report	11.0	7 Sept 76	30 Dec 76
13.	SEADYN Manual and Technical Report	8.5	21 June 76	7 Oct 76*

*Summary Technical Report - User's Manual integrated into deliverable Number 10.

The delay associated with work package 1 can be traced in part to some lack of clarity in the work statement. There is a confusion in the use of the terms "design" and "analysis". Although the activity is designated to provide an analysis capability, a more careful reading reveals it is primarily a synthesis capability that is expected. This is apparent in the requirement to select mooring leg sizes, anchor locations and various mooring components. The confusion is heightened by the fact that a static analysis capability is required as an integral part of the dynamic analysis.

It should be emphasized that synthesis and analysis are two fundamentally different problems. The synthesis problem can be addressed in an implicit manner by iterative application of an analysis algorithm. This requires the development of an evaluative logic and a controller for the iterations. The controller may be a simple trial and error open-loop procedure with the design engineer making the evaluations and generating trial designs, or it could be a sophisticated closed-loop nonlinear programming algorithm. The statement of work indicates some limited closed-loop capability was required. Explicit design procedures, on the other hand, attack the synthesis problem directly and have little or no analytical capability. Explicit procedures are much more economical, but they tend to be special purpose in nature and limited in scope.

The dual nature of the requirements was recognized from the beginning and an attempt was made to meet both requirements with one analysis model. This meant that implicit design procedures were required to be developed to meet the synthesis requirement. By late December it became clear that implementation of an implicit design procedure required complex and uneconomical nonlinear programming techniques. Early in January it was decided to abandon this approach, salvage the static analysis effort to be integrated into work package 2, and formulate an explicit design procedure to meet the synthesis requirements of work package 1. The DESMOOR program was the result.

The delays in work package 1 were virtually erased in the initial effort on work package 2, when two other difficulties were encountered. The first of these was associated with the GFI data from the NSRDC Ship Motion Program.

From the beginning it was recognized that the ship's motion data file generated by DTNSRDC would not be available on the GE computer in Syracuse. It was planned to establish remote access to the CDC 6700 computer at DTNSRDC and use the file there. Incompatibilities in the hardware at Syracuse precluded the use of the remote access link and it was decided to go to Bethesda periodically to use the data for checkout. The first of these trips occurred 23 June 1976. It proved to be somewhat awkward in getting the bugs out in both the Ship Motion Data File and the DSSM program. Computer turn around problems at DTNSRDC contributed somewhat to the delays.

Major delays were caused when it was found that significant numerical errors were encountered in the solutions of the sparse simultaneous equations. The problem was traced to minor logic errors in the solution routine (not developed on this project) and the general ill-conditioned nature of the ship-moor equations. More than a month was required to ferret out these problems and overcome them. When it became obvious that the final delivery dates could not be met, a request for a two month extension was submitted. (A portion of that extension covered the vacation of the principal investigator.)

In working out the details of work package 2, it became clear that many of the features of the SEADYN program were required in the DSSM effort. In April 1976 it was decided to integrate the DSSM program into the SEADYN program. This decision caused work package 3 to be absorbed into work package 2. Therefore, the apparent slippage of schedule on work package 3 is simply a reflection of the integration of the two efforts.

The integrated SEADYN/DSSM program took its final shape in August and September of 1976 with the development of a new solution routine for sparse simultaneous equations and the introduction of double precision strain calculations. Check out proceeded through October with the static portions being checked out in Syracuse and dynamic solutions (including drift force iterations) being checked out during trips to Bethesda. Some delays were attributable to problems, encountered in keeping the two versions (Syracuse and Bethesda) of the program updated. During this period improvements and corrections were also being made

in the program which generated the ship motion data file at DTNSRDC. Various programming, input and analytical errors continued to be uncovered in both programs through November and early December as attempts were made to evaluate the demonstration runs.

In early May the SEACON construction barge was identified as the primary vessel to be used in the DSSM program acceptance and demonstration activities. The first ship motion data from the DTNSRDC program was made available on 23 June 1976. It was in the form of an abbreviated file (only two wavelengths) for a series 60 merchant ship. The file was provided to allow checkout of the dynamic portions of the DSSM program to proceed while the data for the SEACON barge was being generated. Initial test runs with this data indicated the wave induced drift force terms were unreasonably high and checkout of the drift force related portions of the DSSM program were suspended until modifications of the DTNSRDC program could be made and the file regenerated. Various updates to the series 60 file were available for the checkout activity in September and October. Drift forces continued to be a problem during this period.

The first access to the SEACON ship motion file was obtained on 20 October 1976. An extended version of the series 60 file was also made available at that time. It was later found that both of these files had to be modified. Final versions of the ship motion files were not established until the last week of November 1976.

A final set of acceptance and demonstration test cases were agreed upon on 5 November 1976. A partial demonstration of the DESMOOR and combined SEADYN/DSSM program was conducted at the DTNSRDC computer center on 12 November 1976. A final presentation on the programs was made at the Washington Navy Yard on 22 November 1976. An error in the frequency domain solution was uncovered during that meeting and the demonstration cases were rerun and delivered to the Ocean Projects Office the following day. As these runs were being completed, DTNSRDC found still more problems with the SEACON ship motion file and the demonstration cases were rerun after the file was corrected.

Program documentation work was begun in July. The DESMOOR User's Manual was essentially complete in August. Some last minute format changes were made in the program to make it more compatible with the SEADYN/DSSM program. Final documentation for DESMOOR was released on 4 November 1976.

Documentation for the integrated SEADYN/DSSM program was 80% complete by the end of October 1976. The final release date was 17 December 1976. This manual represents a total integration of the static and dynamic moor analyses of work package 2 and the SEADYN program of work package 3.

4.0 DISCUSSION OF THEORY

The overall purpose of this effort was to formulate procedures to aid in designing mooring systems for ships in deep waters. The state-of-the-art does not allow a direct approach to the synthesis of such a system which is highly non-linear and must resist complex dynamic loads from winds, currents and waves. Even when the responsibility for postulating trial designs is placed in the hands of a design engineer, he is faced with a formidible problem in determining if a trial design satisfies the constraints on the system. Non-linearities in the system make analytical evaluations quite difficult when it is attempted to preserve a meaningful level of generality in the problem.

The important non-linearities are listed below:

Geometric Non-Linearity: The mooring lines and other cable components may experience large displacements (particularly in response to quasi-static loading) which requires the treatment of force equilibrium in the deflected state rather than the initial state. The small displacement assumptions of linear elasticity are not valid.

Position Dependent Loading: The loads applied to the system depend on the displacements. This is the classical non-conservative loading problem. Drag loads on the lines, buoys and ships are all in this category. The magnitudes and directions of the load components depend on the orientations of the various parts of the system relative to the flow field. A related effect is a position dependency in the apparent mass of the system which is due to the lack of fluid added mass in the direction tangent to a mooring line.

Non-Linear Drag Loading: The magnitude of drag loading components depends not only on the orientation relative to the flow but also on the square of the relative flow velocity. Furthermore the drag coefficients may also be a function of the relative velocity (Reynold's Number dependence). These effects represent non-linear damping terms in dynamics.

Material Non-Linearities: Typical mooring line constructions have non-linear stress/strain relations. Another effect which can be treated as a material non-linearity is the virtual inability of mooring lines to support compressive loads.

Position Dependent Boundary Conditions: Physical limitations may be imposed on the motion or position of portions of the system by the water surface, bottom or other obstructions. These are usually conditional constraints which are functions of the systems position and/or the applied loads. For example buoys (or ships) must remain at the surface until the resultant loading is sufficient to overcome the total buoyant force.

Accurate treatment of all of these effects requires very detailed and sophisticated non-linear models. In some cases, general purpose non-linear models are not available or are so costly to apply that their use is prohibited. The finite element method offers a very convenient and highly general approach to modeling the mooring lines. It has been demonstrated [2] that it is possible to deal with all of the non-linearities mentioned above with a realtively simple straight-line element. Higher order elements are available [3] but their use does not seem justified at this point. Increased accuracy is available in the finite element method simply by increasing the number of elements in the model. It should be obvious, however, that increased accuracy means increased cost.

Reasonably compact bodies such as buoys, anchors, instrument packages, etc. can be modeled as lumped rigid bodies and their effects can be accommodated readily into the finite element model. Bodies such as mooring or surface buoys and ships present a more formidible problem. Full non-linear treatment of these components involving currents, winds and waves is beyond present feasibility. Linearized models for responses to regular harmonic waves are available (see Reference 4 and Letter Report 7). These presume the motion of the body is small (i.e., an incremental displacement from an initial reference state). The motion equations obtained through such a model are pseudo-linear and depend on the wave frequency and amplitude. Treatment of the effects of winds and currents on these bodies usually presumes static conditions with loads evaluated in a semi-empirical manner.

A general scheme for analyzing the response of a given mooring system within reasonable technical and economic constraints takes the following form. First, it is necessary to separate static and dynamic effects. Those effects treated as static are the ones which tend to produce the most pronounced non-linear responses: wind, currents, working loads etc. Adjustments can be made in the magnitudes of these loads to compensate for any dynamics that may be

ignored in the statics assumption. Static analysis of these effects should deal with the full range of non-linearities. The surface bodies (ships, buoys) are treated as rigid and are constrained to remain on the surface unless the imposed loads exceed their buoyancy. In the case of ships, this means the vessel is restrained in heave, roll and pitch and free to move (under the mooring restraints) in surge, sway and yaw. Similar restraints are imposed on the surface buoys.

The only dynamic effect treated in the mooring analysis is the steady-state response to surface waves. It is assumed that the motion is an incremental change from the static reference state. The waves are described via a wave spectrum in conjunction with a specified frequency increment and interval. The motion equations for the ship are pre-calculated and cataloged on a storage file under relative wave heading, wave length and wave amplitude. The appropriate equations for the state being analyzed are obtained by interpolation in the available data. The buoy equations are calculated using the procedures outlined in Letter Report 7 and in Reference 5. The appropriate incremental equations for the mooring system are generated using finite element techniques. In addition to incremental stiffness and mass terms the mooring system provides damping from the structure and from movement in the fluid. The details of these terms are given in Reference 5. In addition to the harmonic wave responses, it is possible to estimate random responses using spectral analysis techniques.

The waves induce low frequency drift forces which tend to move the system to a new configuration. The effects of these forces are treated as additional static loads in the system. Since these forces depend on the response to waves they cannot be estimated until a wave solution is obtained. This leads to an iterative procedure in which the static solution is repeated after the drift forces are obtained. The wave response calculations could then be repeated for the new configuration until successive estimates of the static reference show insignificant change.

Although the ability to analyze the response of a given mooring system to wind, current, work loads and waves is a most significant achievement, it by no means solves the entire problem. Previous recognition has been made that the real problem is to describe a mooring system which will perform adequately in a given environment. The overall objective is synthesis (i.e., the design of a

mooring system) not analysis (the evaluation of a given system). The analysis is only a tool to aid in solving the primary problem.

A properly posed synthesis problem quickly leads to the requirement for solving an optimization problem with non-linear constraints. This is so, even if the model for the system is linear. Some progress has been made in solving such a problem numerically using non-linear programming techniques [6] but the costs and complexity of such an approach tends to be large. The techniques involve iterative analytical solutions. When the analytical model is non-linear (as in the DSSM case) the solution costs can be excessive. Development of such procedures is not a trivial task either. A significant problem in applying the non-linear programming approach is the formulation of an appropriate merit function. One must be prepared to define specifically (and with a minimum set of variables) what is meant by an optimum solution. The development of such an approach is well beyond the scope of a project such as the DSSM effort. (It should be noted that this effort was not intended to undertake significant development activities.)

The non-linear programming approach falls in the general category of implicit design procedures. An implicit procedure uses an analysis in an iterative fashion in conjunction with an evaluator and a generator of trial designs. As mentioned previously, this may be done in an open loop (the design engineer is the generator of the trial designs and to some extent is the evaluator) or in a closed loop form (non-linear programming).

The sythesis problems can be stated in explicit terms in a few very simple situations. This always requires the governing equations to be expressed in a closed form which is capable of being expressed in terms of the major design variables. Situations where this is possible are very limited. Highly idealized conditions are required and much of the generality must be sacrificed. Because of these limitations, explicit design procedures are usually applied only as a preliminary design tool. Much of the needed detail and generality is then developed in a more-or-less open loop implicit procedure with an enhanced preliminary design as a starting point.

It was recongized from the beginning that no explicit procedure was available for the entire design problem including the dynamic effects. Furthermore, available explicit procedures [7] for static loads were unable to provide the

full generality required for a realistic DSSM design. The Statement of Work makes it clear that work package 1 was intended to provide design capabilities (synthesis). The wording also implies that analysis functions were required. The requirements of work package 2 could only be met with a static analysis integrated with the dynamic analysis. Recognizing that explicit design procedures do not provide an analysis capability nor do they allow sufficient generality, the initial approach to work package 1 was to develop a static analysis capability within the frame work of the SEADYN finite element program and seek an implicit design approach compatible with it. The analytical development met with success but the search for an appropriate implicit design procedure did not. The procedures simply required too much development and promised to be very uneconomical to use. Therefore, the design feature of work package 1 was separated from the analysis and the DESMOOR computer program was the result.

The entire analytical requirements of this project were met within the framework of the SEADYN computer program. Not only was the non-linear static analysis analysis capability for dealing with moored ships in complex configurations provided, but the frequency domain solution for responses to waves was also included in the program. This was done without diminishing the previous capability of the program. In fact some significant gains were made as the result of the full integration (see Letter Report 9).

It should be noted that the SEADYN program provides a time domain analysis capability which is unique. This capability existed prior to the current contract effort. Exclusive of the cases involving ships and buoys interacting with surface waves, the program can calculate transient non-linear dynamics of lines and lumped bodies subjected to time varying forces, currents and or imposed motions in three dimensional space.

In recognition of the role an analysis program plays in the design process, a special feature was added to the SEADYN/DSSM program. An option is provided which aids the designer in his evaluative function. The program can compare the loading of lines, buoy and/or anchors with the capacity of those components.

The next section disucsses some of the features of the DSSM design and analysis implementation. Deatils of the equations and numerical procedures used are covered in the Letter Reports and the User's Manuals for the DESMOOR and SEADYN/DSSM programs [5, 8] .

5.0 DISCUSSION OF IMPLEMENTATION

5.1 Static Loads on the System

Three categories of static loads are dealt with in the DSSM problem. They are gravity loads (including buoyancy effects), working loads, and environmental loads such as wind and current effects.

Gravity loads are used in the definition of the quiescent state of the system and remain active through all of the analyses. They are treated as simple point loads for buoys, anchors and other lumped bodies. The gravity loads for line elements are treated by the usual finite element procedure to obtain nodal point equivalents of the distributed loads. Gravity loads for the ships do not appear explicitly in the analysis since it is assumed that the ship is initially in equilibrium with the gravity loads in balance. All ship's motion are assumed to be incremental changes from the initial state. Static analyses involving shi, either assume the ship is constrained on the surface or allow incremental movement acting against input values for the incremental stiffness matrix. The frequency domain dynamic analysis assumes incremental motion.

Working loads are treated as nodal point loads. They may be applied in the static analysis to determine the reference state for the frequency domain analysis. They may be applied to any node in the system for static analysis but only to the ship in the static design program.

Wind and current loads may be applied to the system at the ship, surface buoys, hawsers and the various subsurface components in the static analysis. Wind and current load may be applied only to the ship in the static design program. The analysis treats wind and current loads on line elements with nodal point equivalents to the distributed load with drag coefficients which may be defined by the user.

Wind and current loads on the ships are obtained either from input load tables or from approximate analytical expressions. The analytical expressions are provided as a convenient alternative to the loading tables, but the user is cautioned that they are not universally applicable. They presume a fine lined hull form and a well proportioned super structure (see Letter Report 3). The tabular form for ship's loads follows the procedures outlined in NAVFAC DS-26 [1] and uses similarity scaling to convert test data from one ship to results for a "similar" ship.

5.2 Static Design Approach, The DESMOOR Program

The DESMOOR program implements an explicit design procedure to obtain trial designs for slack (catenary) moors and taut (neutrally buoyant) moors. The theoretical details are given in the user's manual [8]. As noted above, the program has limited scope in that it was not possible to include the full generality available in an analysis program. The design of slack moors uses the classical closed form catenary equations [7] and selects mooring legs which will support the required loads and restrain the ship within a specified excursion radius while remaining tangent to the bottom. The catenary equations assume inextensible uniform lines with uniform distributed loading acting only in one direction (gravity). Other external loads are allowed only at the end of the catenary. These limitations which are inherent in the closed form governing equations are unavoidably imposed on the design program. The governing equations for taut moors assume weightless uniform lines which resist the external loads by elastic deformation. Whereas the catenary equations allowed the anchor position to be determined in the design, the taut line equations require the anchor positions to be specified. Both procedures require a specification of the number of legs and the heading of the lines relative to the quiescent position of the ship.

Specifically excluded by the governing equations of the static design procedue are moors with non uniform legs (e.g., double catenary, tapered lines, intermediate floats or weights, etc.) and systems subjected to loads applied anywhere but at the ship. Specifically excluded by the numerical procedures used in the DESMOOR program are designs with different depths at each leg, moors with different properties at each leg, etc.

The catenary equations tend to give unrealistic lengths for shallow waters. This is because catenary moors develop their load reactive capability by a change of shape rather than by elastic stretch. In the shallow water case shape change is less effective and the resulting design is a long shallow catenary which resists loads by picking up long lengths of line from the bottom. As a rule of thumb, designs with scopes (ratios of line length to water depth) greater than 7 should not be used.

The taut moor equations can be rendered invalid by specifying an excursion limit that is too loose. This shows up in the design results as a statement that the design conditions can be met with a negative initial tension. The DESMOOR program will automatically reduce the excursion limit and rerun the design case when this is detected.

The implementation of the design procedure requires the user to select the number and position of the mooring legs, decide whether it is a slack or taut moor, specify if hawsers and mooring buoys are used, identify what heading range the worst loading is expected to be in, and select the heading increment to be used in searching that interval. The wind and current are then assumed to be coincident with headings in the interval specified. The worst condition found is presumed to be the controlling condition for the design. This then is not a fully closed-loop design procedure since it leaves some important judgemental functions in the hands of the user.

5.3 The Static Analysis Approach

Unlike the static design approach, the static analysis allows very general mooring situations to be dealt with. Lines may be non-uniform with arbitrary arrangements, intermediate bodies, non-uniform combined loads, etc. Both the geometric and non-linear elastic responses of the lines are included. Anchor points may be at unequal depths as long as bottom interaction limits are not imposed (the program allows only one surface and one bottom limit).

Two basic problems are encountered in the static analysis of mooring responses. Both of them come from the numerical procedures used and are aggravated by the physical characteristics of typical mooring systems. The first is referred to as the initial configuration problem or the zero-preload problem [2, 5] . The second is the convergence characteristics of the modified Newton-Raphson (MNR) solution routine. The following discussion will show that the two problems are related.

The inherent flexibility of cable systems leads to the requirement that the cables must be preloaded in order to develop structural stability. Due to the geometric non-linearity of such systems it is difficult to estimate the configuration of all but the simplest of systems under the action of internal preloads. It usually is a very difficult task to define a set of preloads and a configuration which represent a numerical description of an equilibrium state of the system. The SEADYN/DSSM program provides for various schemes to aid in getting an initial configuration which is in equilibrium. They are described in the user's manual [5] and in reference 2. Unfortunately they are of limited effectiveness; i.e., they will work in some situations but they are not foolproof. The most effective approach for mooring situations was developed in this contract effort. It is the catenary input generation scheme described in the user's manual. In order to apply it, one must have an initial estimate of the quiescent state of the ship and moor. This means the location of the ship and the anchor points must be defined, along with the weight per unit length of the lines and the initial horizontal component of line tension at the surface. The input scheme will then divide the legs into elements and estimate the initial tension in each element using the catenary equations. The DESMOOR program is very useful in obtaining this initial data. The initial configuration obtained by this approach has been found to be very close to the final equilibrium state for the quiescent configuration.

When mooring buoys are used to support the mooring line and are connected to the ship through a hawser, there is an ambiguity that must be resolved in defining the quiescent state. The lines are not all attached to the same point on the buoy; therefore, loads in the lines will cause a change in the orientation of the buoy. This level of detail is not treated in the static design procedure, but it is treated in the static and dynamic analyses. Mooring buoy rotational terms were retained in the analysis since it was felt the wave excitation of the buoys may have a significant effect on the mooring line tensions for short wave lengths.

When the initial configuration of the system is described to the SEADYN/DSSM program it is necessary to get a good estimate of the angular positions of the mooring buoys. The design program gives sufficient data to make a reasonable estimate of the buoy position. The required information is the tension and inclination of the mooring line at the buoy attachment and the positions of the mooring line and hawser attachments on the buoy. Since the dynamic analysis equations approximate the buoy as a sphere, a reasonable approximation is that the lines attach on the buoy surface at diametrically opposite positions. The equations of static equilibrium can then be used to solve for the angular position of the buoy. A sample calculation is given below to illustrate the procedure:

GIVEN: Vertical and Horizontal Components of line tension at the buoy (V, H), and the buoy radius, R.

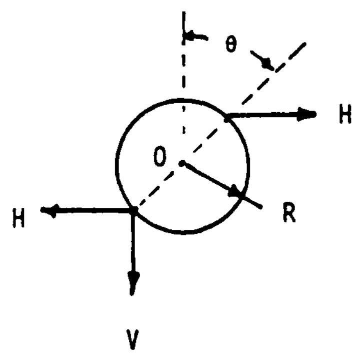
SOLVE FOR θ:

$$\Sigma M_O = 0$$

$$2\ H\ R\ \mathrm{Cos}\ \theta - V\ R\ \mathrm{Sin}\ \theta = 0$$

$$\frac{\mathrm{Sin}\ \theta}{\mathrm{Cos}\ \theta} = \frac{2H}{V}$$

$$\theta = \mathrm{arc\ tan}\ \frac{2H}{V}$$



The coordinates of the buoy center and the attachment points are required by the SEADYN/DSSM program. The center coordinates are available from the input to the design program, and the attachment coordinates can be calculated from the data above.

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The second problem that is encountered in the static analysis is associated with the numerical stability of the solution procedures. The static solutions depend on the tangential or incremental stiffness matrix to estimate the deflection from one configuration to another. When the stiffness matrix is singular (as in the case with zero-preload elements) there is no way to solve for the displacement increment. When the stiffness matrix is ill-conditioned (nearly singular) it may lead to significant errors in estimating the displacement increments.

Iterative solutions attempt to correct for the errors associated with the position dependent non-linearities, but they may fail if the equations are severely ill-conditioned or if the step size is too large for the non-linearities involved. Decreasing the step size is usually the answer, but in some situations the convergent step size is so small that the numerical error inherent in the numerical procedures and the computer word size may be of the same order as the displacement increments. Convergent solutions cannot be obtained in this situation by decreasing the step size, and some other method of getting an estimate of a configuration which is close to the final equilibrium state is needed. Schemes such as over-estimating the stiffness (numerical damping or artifical preloads) or searching schemes, which work from the pattern of successive estimates to project a better estimate, offer some hope. Limited capability in this area is provided by the MNR solution in the SEADYN/DSSM program, but more development is needed before a fully effective procedure is found.

Characteristics of the ship's mooring problem which aggravate the static convergence problem are found in the angular stiffness terms in both the ship and mooring buoy equations. In both cases the bodies are assumed to be rigid and develop their resistance to angular motion from the line tensions and the geometry of the attachments. For example, the yaw resistance of a ship comes from the horizontal components of the mooring line tensions. In a typical deep sea moor the mooring lines are nearly vertical at the surface and the horizontal stiffness is quite small in comparison with the axial or vertical stiffnesses. Thus it takes relatively large tension and/or angle changes in the lines to resist a change in yaw moment. In contrast, the flow induced yaw moments are quite sensitive to the yaw angle. This leads to the unfortunate combination of low stiffness and highly position dependent loading. This combination means highly sensitive convergence behavior.

Besides being a source of numerical stability problems, this situation signals a potential for physical instability. It is intuitively obvious that a moor with poor yaw restraint must move through large angles in response to yaw loading (e.g., the single point moor). If more than one line is used there is a possibility of the ship twisting the lines together under high loading. The SEADYN/DSSM program is incapable of sensing if this occurs. Extensive development would be required to include this capability. Whether or not a physical instability is present can be investigated with the program by the selection of critical loading situations and following the response with small steps to see if the lines reach a state where they would interfere with each other.

The angular stability problem is more acute in mooring buoys than in ships because of the short lengths involved. In general the lever arms which develop angular stiffness from linear stiffness are an order of magnitude larger in ships than they are in buoys. Although the buoy will not be subjected directly to highly position dependent loads as the ship is, the buoy will develop high angular responses to small changes in line conditions. Couple this with the need for large line changes to resist ship loadings and the numerical stability problem comes into focus. When the iterative solution is not producing estimates close to the final state, the successive estimates of buoy angular positions could be quite erratic. For this reason it is recommended that the initial attitude of the buoys be calculated using the procedures outlined above and then constrain the buoy angular motion in all but the yaw direction during static analyses. The user's manual [5] and the demonstration problems [9] should be consulted for the means of accomplishing this. These constraints are automatically released in frequency domain dynamic analyses. This procedure avoids numerical convergence problems in the static analysis and still gives a reasonable estimate of the incremental dynamic response.

A poor estimate of the buoy initial position can lead to poor convergence behavior even when the angular components are constrained. This is caused by the presence of an irreducible error in the force equilibrium. This can be seen in a non-decreasing residual norm even though the displacements have converged. The input for the buoy position and line preloads should be checked when this occurs. An increase in the residual convergence tolerance may also be considered.

Various controls are provided in the SEADYN/DSSM program which can be used to "tailor" the MNR solution procedure to the problem. These include the residual and displacement error tolerances, the upper limit on the number of iterations before the step size is reduced, the lower limit on the number of steps to convergence before the step size is increased, the sequence used in recalculation of the stiffness matrix, the use of numerical damping, the use of a one-dimensional search approach, and the number of trials before the iteration is aborted. Descriptions of each of these are given in the user's manual [5]. A selection of a set of values for these controls for a given situation fall within the art of solving non-linear equations. Hands-on experience is required to develop the ability to make judicious selections of the control parameters. The program has a set of default conditions built-in which are selected if not superceded by input data. These values represent a reasonable starting point if no previous experience is available.

When an iterative solution fails there are a few things that can be checked to identify the cause. Seeking to understand the cause will generally give some clues on what to do to get convergence. Typically the aborts will take one of three general forms. Each of these are discussed below with some possible remedies.

1 - The limit number of iterations was exceed after repeated step size reductions: Look at the residual and displacement norms. If the residual norm is large while the displacement norm appears to have converged then there is an equilibrium problem. This usually means the system has been improperly defined ---- check the input data for consistency. If the residual norm is small but not small enough for convergence and does not appear to be decreasing then a larger residual error tolerance may lead to convergent solutions. Other possibilities are a poor starting configuration, step size far too large, or displacement error tolerance too large. If, on the other hand, the residual appears to have converged but the displacements have not then one has a slowly convergent problem requiring smaller step sizes or perhaps there is insufficient stiffness (preload and/or geometry) or the loading is too severe or improperly defined. In these situations a smaller step size is usually required, but modifications of the sequence that the stiffness matrix is recalculated, the use of a one-dimensional search and/or the appropriate use of numerical damping may

help. In the case of numerical damping, slow convergence results from large numerical damping while erratic behavior (usually signaled by increasing displacement norm) can be reduced by a larger numerical damping factor.

2 - The equation solution failed successively: There will usually be gross input problems involving zero-preloads, geometry errors or large loads. This abort is a signal of singular or grossly ill-conditioned equations.

3 - The buoy/anchor moves too far beyond limits: This occurs when surface and bottom limits are imposed and one of the bodies approaches the limit and then moves well beyond it in the next step. This usually is a signal that the step size is too large and the program will automatically reduce the step the limit number of times. Given that there are no input errors (i.e., preloads, geometry etc) this means that the loads are sufficiently large and the response is sufficiently soft to require much smaller steps to get the body accurately constrained at the limit. This limit is determined by the surface or bottom coordinate and the diameter of the body. The message is triggered when the body overshoots the limit more than four diameters. The body diameter can either be increased, the step size decreased, or the number of tries increased. This situation can often occur in a rapidly convergent problem where the limit is reached after a number of steps which have lead to step size increases. Over-optimistic step size increases can be controlled by reducing the limit number of iterations.

One of the signficiant mooring non-linearities treated in the static analysis is the effect of mooring lines interacting with the bottom. The program recognizes only one depth associated with this feature (i.e., the bottom is flat and parallel to the surface). A typical slack moor will have a significant amount of line on the bottom in the quiescent state. Usually only one leg will lift much of the line under even the extreme conditions. For this reason, modeling all of the line on the bottom for each leg may not be necessary. The detail which is used near the bottom should be given careful consideration mainly for economic reasons. Including a large number of elements where many of them are on the bottom can add greatly to the cost of computation but contribute little to the overall results. This is especially true if the critical components are at or near the surface.

The program allows the flexibility to treat the bottom interaction with great detail, to ignore it, or to make some approximation between the two extremes. It is left to the user to decide how much modeling detail is appropriate for his application.

5.4 Dynamic Response to Waves

The implementation of the frequency domain solution for regular wave responses was relatively straightforward. The major problem encountered was in the development of a linear solution routine which deals with linear complex equations which are symmetric and banded. The factors influencing this problem were storage requirements and numerical efficiency with ill-conditioned equations. The storage problems were met by developing a solution routine which used a compacted storage format and by overlapping the use of COMMON [10]. The effects of ill-conditioning (due primarily to the ship's yaw equation and buoy rotations) were dealt with by adding double precision calculations on the separate real and imaginary parts of the coefficients.

Some minor problems were encountered in establishing a compatible interfacing of the SEADYN/DSSM program and the ship motion file. This type of problem is not unexpected in a project of this complexity. They were dealt with in the normal course of program checkout.

The development of the buoy motion equations required considerable idealization since the state-of-the-art does not allow for general buoy shapes at arbitrary positions relative to the wave. The buoy equation development presented in Letter Report 7 and reference 5 assumes the buoy is modeled as an equivalent sphere with its center of gravity at the center of the sphere and the still water surface bisecting the sphere. The arbitrary angle requirement is due to the fact that the static loads will cause the buoy to assume an attitude other than upright.

Damping effects treated in the frequency domain equations are those associated with the wave interactions with the ship and mooring buoys and those related to the internal nature of the mooring lines and the external reaction with the fluid. The internal damping of the mooring system is treated in the customary manner by assuming the damping matrix is proportional to the mass and stiffness matrices. The external damping was linearized following the development given in Reference 5.

The most troublesome aspect of the response to waves is the quasi-static effects of the wave induced drift forces. Beyond the problem of getting a finalized definition of the force coefficients mentioned earlier, the magnitudes of the forces present some difficulties. The program treats the drift induced forces

as additional static loads on the system. The magnitude of the accumulated drift forces for a typical wave spectrum turn out to be of the same order of magnitude as the static forces from wind and currents. Application of the additional drift forces (the yaw moment in particular) opens the door for further convergence problems. Further discussion on the subject will be deferred to Section 6.0 where the program checkout activities are discussed.

5.5 Component Adequacy Checks

The component adequacy check option of the SEADYN/DSSM program required the development of a procedure for getting from the single tension estimate given for each element to estimates of the forces at the ends of each element. Discrete element modeling with simple straight elements and nodal point forces does not give the nodal point forces directly. The procedure for getting them is outlined in Reference 5. The end load estimates are used in determining the resultant loads applied to the buoys or anchors. Checks for adequacy then compare the resultant with capacity data given as input or obtained from the same component inventory data as used by the static design program. The procedures given in DM-26 [1] are used in calculating anchor capacity.

6.0 CHECKOUT AND VALIDATION

The details of the checkout and validation effort on the DESMOOR and SEADYN/DSSM programs are given in the Acceptance Report [9]. Discussion in this section will be confined to some commentary on that activity.

It should be recognized that the process of developing and checking out any computer program of even moderate complexity is a non-linear process. One simply is not able to start at the beginning of the effort and proceed in a straight line to the end and come out with a fully checked out program. In spite of the best of intentions and the most careful planning, there will be false starts, altered approaches and new insights developed in the process of completing the program. A most enlightening essay on this subject is given by Griffin [11]. This article should be on the reading list of anyone involved with software development. It is Griffin's contention that major computer programs may never be absolutely checked out due to multiplicity of logic paths and varying levels of parameter sensitivities combining to present an astronomically large number of situations that must be checked. By careful planning one can exercise the major combinations and eliminate many of the gross errors. Most of the remaining errors are usually found in a trial and error process over months or years. The process can be accelereated by wide dissemination and communication between users. The checkout process becomes even more difficult when few (if any) known solutions are available or if test data is skimpy.

The SEADYN/DSSM computer program is much more than moderately complex and it deals with an amazing diversity of physical situations. Test cases supported by independent solutions and/or test results are indeed limited. One should not be surprised, therefore, if "little bugs" are found from time to time. The checkout process has been quite extensive and in some cases errors have been found and corrected which have been in the program or its antecedants for some time. A vivid example of this is the routine used for solutions of linear simultaneous equations. This routine was the focal point in the efforts to deal with the numerical stability problems in the static solutions. This routine was developed prior to the SEADYN program, and before it was used in SEADYN it was tested on linear equations with known solutions and found to give accurate results. Unfortunately those test cases were well-conditioned and they did not detect a minor programming error.

During the numerical stability investigations the error was found in addition to identifying the need for accumulating sums of products in double precision. After revision of the routine a marked improvement in numerical stability was obtained.

An attempt has been made to exercise all of the major logic paths of both the DESMOOR and the SEADYN/DSSM programs. The DESMOOR loading and catenary calculations and the component selection procedures have been checked against hand calculations. The design loops have been followed through in detail and all appears to be in proper order. Design solutions have been obtained for various combinations of constraints and have been evaluated for reasonableness. A compatibility in the ship loading calculations was maintained in the two programs. The same set of ship loading data can be used by either program.

A number of test cases were exercised on the SEADYN program prior to the DSSM activity [2]. The majority of these were rerun on the SEADYN/DSSM program to verify the previous capability was preserved. Solution improvements were noted in the static solutions. Some of these test cases are presented in the User's Manual [5].

Considerable effort was expended in checking out the ship dynamic response calculations. Unfortunately this effort had to be curtailed somewhat due to the lack of a timely delivery of a finalized version of the ship motion data. A total of seven demonstration cases were run on various mooring configurations of the SEACON barge. These included two four-point slack moors, a single point slack moor, and two four-point taut moors. Drift force induced corrections to the static configuration was accomplished only on the single point mooring case. Attempts were made to run with drift force effects on other configurations but convergence problems were encountered because of the large yaw moment induced by the drift forces.

It was concluded from the demonstration cases and the checkout runs on the series 60 vessel that the solutions for unrestrained ship responses were essentially the same as those obtained in the DTNSRDC ship motion program [4] and that moored ship responses followed reasonable patterns. No control data is available to give direct verification of the moored response calculations. No previous solutions have been published and a search for test data was unsuccessful. Solutions for line tensions were verified by comparing peak response estimates with a non-linear time

domain solution for a single leg driven by the harmonic motions predicted by the frequency domain solution. Abnormally high tensions were obtained for hawser lines attached to mooring buoys. The source of these tensions have not been identified, but the mooring buoy equations might be considered suspect since line tensions appear reasonable in other situations and there has been no independent verification of the buoy response calculations.

7.0 AREAS FOR FURTHER DEVELOPMENT

This effort has identified a number of aspects of the design and analysis of mooring systems that deserve further pursuit. In addition, renewed attention has been given to previously identified development areas.

7.1 Static Design Improvements

The functional separation of the design aspects from the analysis program appears to be a reasonable approach. DESMOOR provides some very effective computational aids at very low cost. A considerable number of design options can be investigated with small amounts of input and very short computer turn-around time. The obvious thing to do with the program is to modify it for operation in an interactive mode on a time-share system. The program is very well suited to this type of operation and it would allow it to be used from convenient remote access terminals.

Improvements in the internal workings of the program should also be considered. The improvement with the broadest effect would be to remove the requirement for specifying the heading interval to be evaluated and implement a searching routine which would identify the extreme situation for the design. This would allow a considerable reduction in the program's output and would remove the uncertainty about the worst loading condition.

Short of introducing the search algorithm, the output for each design trial could be put on an optional status to reduce the output. If this is done it would be necessary to check each design trial and save the results for the controlling one so that it could be output with the final design results.

Generalization of the design procedures to deal with non-uniform legs, multiple depths and more complex legs (e.g., double catenary) could prove to be considerably complicated. Some stuides could be done to identify what generalizations (if any) could be readily made.

Some generalization and standardization of the component inventory format could be achieved. With a little effort the inventory could be made more susceptible to modification and expansion.

The buoy attachment coordinates calculations could easily be made within the DESMOOR program. This could be done if the data for the controlling case were saved until after the component selection. Direct coupling of the DESMOOR program with the SEADYN/DSSM program does not appear to be a reasonable pursuit. This is due mainly to the limitations on generality imposed by the explicit design procedure. Modeling judgement is required in generating SEADYN/DSSM input from DESMOOR results.

7.2 DSSM Analysis Improvements

It is somewhat difficult to identify improvements to the SEADYN/DSSM that specifically relate to the DSSM problem. This is so because the DSSM features are such an integral part of the program. The major problems in the DSSM analysis are associated with the static analysis convergence problems. This affects the amount of effort it takes to get a good starting configuration, a good static reference for the frequency domain solution, and the ability to modify the static reference to reflect drift force effects. An immediate improvement in the static convergence characteristics should be possible by adding the ability to apply numerical damping to selective components. This would mean that appropriate resistances could be added to the ship's yaw and the buoy rotation terms and allow a reduction of the ill-conditioning by working directly on the critical terms. Some additional improvements may be possible through the use of better convergence accelerating schemes. Realization of these improvements will require more careful study of the behavior of the MNR algorithm.

Alternatives to the MNR procedure may have some more desirable characteristics. One possibility exists in the sequential search algorithms. These methods also show some promise in dealing with the initial configuration problem [2]. Continued study should be applied in the area of alternative static solution procedures.

Detailed checkout of the frequency domain solutions should continue. The equations for buoys should receive special attention. More general buoy forms should also be sought. The programming of the frequency domain solution presumed that the calculation could be done with only a buoy (or buoys) in the system (i.e., with no ship). There was no opportunity to adequately pursue this option and check it out (there was no contractural requirement nor funds). This should be done.

Alternative sources and uses for the ship motion file data should be pursued. The present approach uses strip theory, but there appears to be no reason why other procedures could not be used. The SEADYN/DSSM program makes no other presumptions about the ship motion file other than its format and the non-dimensional form of the coefficients. Either or both of these could be altered with minor impact on the program.

The ability to restart the frequency domain solution may prove to be useful. Two possibilities might be considered. The first is the restart of the regular wave solution to continue the calculations for wave lengths beyond those obtained in the previous run. The second is to start from the response amplitude operator file and proceed with a regular wave evaluation of the motion components or to perform the final stage of superposition of regular wave results for random response calculations. The latter seems to be more likely to be useful.

Other improvements to the frequency domain model might include short crested wave effects and the treatment of the slowly varying portion of the drift forces. Continued attention should be paid to the drift force calculations.

The overall importance of the wave induced dynamics should be studied. The analytical approach may prove to be useful in identifying factors to be applied in the design phase which would approximate wave induced effects. That this is probable is suggested in the DM-26 procedure of factoring the wind loads to compensate for the neglect of dynamic effects. The utility of an apporach such as this is expected to be more in the preliminary design realm rather than replacing the use of the SEADYN/DSSM analysis as an aid to final design verification.

7.3 General Improvements to SEADYN/DSSM

Beyond the improvements in the static solution procedures mentioned above, there are a number of other useful improvements that could be made. Two items high on the list are line deployment capability (payout/reel-in) and plotting capability. Preliminary work on the deployment feature has been done . Plotting capabilities can take various forms from simple geometry plotting for input checking to graphic display of the results.

Various areas for pursuing program improvements were outlined at the close of Reference 2. Some of these have been addressed in this contract. Specifically the DSSM capability, the removal of problem size restrictions, and the introduction of multiple media effects (air and water) are items that have been addressed. More could be done on the multiple media feature. The present capability requires that the fluid medium for each element be identified and it is assumed that no element moves from one medium to the other. This means that an element which starts out in air is assumed to be in air throughout the entire analysis regardless of the position of the nodes. A capability for estimating the loading as an element traverses the water/air interface should be provided to make the multiple media analysis more realistic.

Other items noted in Reference 2 that are worthy of pursuit are listed below:

1 - Addition of other elements, large displacement bending, coupled extension-torsion, others.

2 - Treatment of internal damping in time domain analyses. The easiest to implement would be the proportional damping approach.

3 - Strumming analysis capability. More study is required before the specific form this capability should take can be detailed, but it would probably include a small displacement dynamic analysis superimposed on a static non-linear analysis. It should be noted that effects of vortex shedding from large bodies such as buoys can be treated now by estimating the oscillating forces and imposing them in a deterministic fashion in a time domain analysis.

4 - The importance of fluid modeling approximations such as the neglect of flow field accelerations and the load rotation terms should be studied. Along with this, the process for linearizing the fluid damping should be reviewed.

5 - Various alternatives in the solution of the time domain dynamic equations should continue to be studied with the aim of reducing computation costs. There is some activity in this area [12] but more needs to be done.

This contract effort made a small step toward aiding input preparation by adding the catenary generation scheme. More effort in this area may be of value. The first thing that could be done would be to generalize the catenary generation to deal with non-tangent and/or double catenaries. Other generation schemes or alternate input forms might be identified and implemented. If a general class of problems requiring specialized input can be identified, the development of input generating pre-processors might be useful.

The slave/master nodal coordinate transformations introducted to deal with ships and mooring buoys can be generalized to be used in time domain analyses. Preliminary work was done in this effort but it was never finalized since it was beyond the scope of the contract. Items needing attention are the transformations to assign masses at the slave nodes to the master nodes.

The non-linear time domain dynamic analysis capability could be greatly extended with the introduction of motions for rigid bodies. This development could either add logic to calculate the body equations or provide for reading the coefficients in a manner similar to what is done for the ships in the frequency domain solution.

The SEADYN/DSSM program presently presumes all calculations are done in 3-D space. This results in some computational inefficiencies when 2-D or 1-D problems are solved. It is possible to modify the storage format and solution controls to avoid the extra terms. This modification could result in some meaningful reductions in computation costs if the restricted problems are solved routinely.

The efforts to obtain experimental verification of the SEADYN/DSSM computations should be continued and expanded to include all of the major features of the program. Meaningful improvements are more readily defined when actual physical data are available to identify the need. Conversely, having confirmation of the accuracy of existing capability is of great value to the design engineer and those who use the sytems he designs.

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APPENDIX A

STATEMENT OF WORK

STATEMENT OF WORK

DEVELOPMENT

OF A

DEEP SEA SHIP-MOOR

COMPUTER SIMULATION PROGRAM

Contract Number N62477-76-C-0002

17 June 1975

Revised 4 August 1975

OCEAN ENGINEERING AND CONSTRUCTION PROJECT OFFICE

CHESAPEAKE DIVISION

NAVAL FACILITIES ENGINEERING COMMAND

STATEMENT OF WORK

FOR DEVELOPMENT OF A DEEP SEA SHIP-MOOR COMPUTER SIMULATION PROGRAM

INTRODUCTION

Background. Various deep-ocean engineering and construction operations require ship-mooring systems to provide specific station-keep capabilities under loads imposed by sea states, sub-surface currents and work loads. A ship-mooring design tool is a basic capability requirement in the acquisition of such mooring systems. This is best provided by a computer simulation program which can serve as an analysis tool to assist the mooring designer in predicting the static and dynamic loads developed in the mooring lines and anchors, verify the station-keeping performance of the moor under the specified loading conditions, and provide cyclic loading data for the estimation of the fatigue life of the system elements.

Objectives. The principal objective of this effort is to develop an interim computer simulation capability for analyzing the design and performance of Deep Sea Ship Moor (DSSM) systems under specified environmental conditions and functional requirements.

The desired computer simulation program shall:

1. Determine the static loads and displacements of a moored ship, and its moor system elements, under arbitrary steady-state wind, current, and workloads.

2. Size the moor components in accordance with selected materials, configuration, functional requirements and design rules.
3. Predict the dynamic loads, drift forces and additional displacement of a moored ship and the selected moor system under arbitrary sea states, and surface currents.
4. Integrate the static and dynamic simulation programs to establish a procedure which analyzes the selected mooring system relative to functional requirements such as watch circle, survival conditions, and life expectancy.

Another objective is to acquire a computerized procedure to solve the transient cable dynamic problems associated with deep ocean cable structure installation and utilization.

Scope. The scope of work includes:

(1) Review analytical formulation for existing computer programs concerning ship-motion and cable-structure dynamics, as well as manuals and design guides for mooring system design; and produce a plan outline and logic diagram for development of the DSSM computer simulation program.

(2) Develop the analytical models suitable for the DSSM computer program and make the modifications required for integration of the existing Navy and G.E. cable

Scope (cont'd.)

(2) cont'd.

dynamics computer program to develop the DSSM program. This will provide interim computer program capability that is developmental in nature and is not intended as a basis for design or design implementation.

(3) Validate the DSSM program using Navy provided computer and consultation support.

(4) Package and document the validated program (s) coded in Fortran IV language for use on the NSRDC CDC 6700 computer.

(5) Package and document an existing cable structure dynamics program, such as SEADYN, with coding in Fortran IV for use on the NSRDC CDC 6700 computer. Validation and maintenance of the SEADYN computer program are not required as part of or subsequent to this contract.

(6) A mooring design, or series of designs, or complete methodology is not expected.

WORK PACKAGE ONE: STATIC-LOAD SHIP-MOOR COMPUTER ANALYSIS PROGRAM

Purpose

The purpose of this Work Package is to develop an analytical model suitable for a computer program which determines the static response of a DSSM to the loadings induced by wind, currents, and working loads of arbitrary magnitudes and directions. The response data is to be used for selecting the moor components in accordance with the design and functional requirements.

Task 1 Definition of Design-Parameter Inputs

A. Define appropriate design parameter inputs required to accurately represent the following categories:

1. Environmental Conditions
2. Ship Geometry
3. External Loading
4. Moor Component Characteristics, including:
    a. Type
    b. Standard Size
    c. Wet Weight
    d. Ultimate Strength
    e. Elastic Properties
    f. Drag Coefficient

B. Perform a tradeoff study between inputs developed from the categories list in order to determine which inputs are essential for use with a computer simulation of the Deep Sea Ship Moor Static Response design problem. The trade-off study is to be performed on the basis of an analysis of the design and functional requirements of a DSSM. The analysis of these requirements should include a consideration of the following characteristics of selected components of the moor system and the design rules. The consideration shall include:

1. Anchor Holding
2. Cable Angle at the Anchor
3. Allowance for dynamic loading increments.
4. Watch Circle
5. Survival Conditions
6. Component Safety Factors

C. Provide a letter report of the results of this Task which includes:

1. A listing of the selected DSSM design parameter inputs with associated units of measure.
2. A description of the analysis of DSSM functional requirements.
3. Trade-off study analysis showing the rationale for the selection of inputs.

Task 2 Development of the Static Ship Loading Analysis

A. Review Chapters 6 and 7, NAVFAC Design Manual 26, for Harbor and Coastal Facilities provided as GFI. On the basis of this review, develop a programable analytical model suitable for the determination of steady wind and current forces and yaw moments acting on a moored ship under various headings. The programmed model shall include algorithms for:

1. Selection of an equivalent ship from the tests of the nine typical ships addressed in Design Manual 26.
2. Adjustment of test data to design velocity.
3. Adjustment of test data to design depth.

B. Provide a letter report of the results of this Task which includes:

1. A mathematical description of the developed model.
2. A logic flow diagram of the developed model.

Task 3 Development of Static Moor Configuration Analysis

A. Review the Designer's Guide for Deep Sea Ship Moorings produced by Hydrospace Research Corporation for NSEC as an example of an iterative procedure for ship mooring design based on catenary configurations. Develop the logic for similar analytic procedures to determine static-load induced displacements of a ship and its mooring system from the parameter input selection and the static ship loading program developed in Task 1 and Task 2.

Task 3 (cont'd.)

B. Develop a static ship-moor analysis computer program based on the above logic which will:

(1) Accept pre-selected single and multi-leg moor instruction consisting of either catenary or taut mooring legs.

(2) Determine the relationship of arbitrary moor displacements to the restoring force induced in the mooring legs of pre-selected material independent of the leg size.

(3) Calculate the resulting forces and moment acting on the moored ship due to the displacement of the selected moor corresponding to the specified watch circle.

(4) Select the size of mooring leg by matching the worst static loading determined in Task 2 with the above forces and moment.

(5) Re-examine the translational and heading changes of the ship due to the displacement of the selected moor configuration with the selected mooring legs under the survival conditions in regards to the watch circle and other moor design specifications.

C. Provide a letter report of the result of this task which includes:

1. A description of the developed iterative procedure with logic flow charts.
2. A source file for the computer program.

Task 4 Development of a Selection Method for Moor Components

A. In accordance with the method and practice described in Chapters 6 and 7, NAVFAC Design Manual 26, develop a logic sequence which enables the selection of mooring components other than mooring legs such as, hawser lines, buoys, anchors, and chain assemblies. Selected components will be of standard size and type as specified by the design parameter inputs determined in Task 1 of this Work Package. The selection method shall reflect the results of the analysis of functional requirements and operational characteristics defined in Task 1.

B. Implement the logic sequence as a computer program which is consistent in units and format and combined with the computer program developed in Task 3 to produce the Static Moor Design Program.

The combined program shall have the capability to: (1) Identify a DSSM configuration and, (2) Identify the necessary components which make up the selected configuration.

C. Provide a letter report on the results of this task, which includes:

1. A mathematical description of the developed iterative procedure including logic flow charts, and
2. A source file for the computer program.

WORK PACKAGE TWO: DYNAMIC-LOAD SHIP-MOOR COMPUTER ANALYSIS PROGRAM

Purpose

The purpose of this Work Package is to develop an analytical model suitable for the computer program which determines the dynamic response of a DSSM to external loads imposed by ship and buoy motions which are induced by waves. This Work Package includes the integration of the Static Ship-Moor Analysis Program of Work Package I with a Dynamic Ship-Moor Analysis Program to produce a comprehensive computerized design procedure for the design of DSSM.

In carrying out the tasks or Work Package 2, the contractor will receive the government-furnished use of the CDC 6700 computer located at the Applied Mathematics Laboratory at NSRDC; including possible remote access, to develop, integrate and validate the DSSM. NSRDC personnel will provide consultation in adapting the DSSM to the CDC 6700, and will provide assistance in gaining access to the NSRDC computer system.

Task 1 Definition of Design-Paramter Inputs

A. Review the design-parameter input trade-off study for the Static Ship-Moor Analysis conducted in Task 1 of Work Package 1, and define the additional design parameter inputs required for a computer simulation of the DSSM dynamic response design problem.

B. Provide a letter report of the results of this task which includes:

1. A listing of the additional DSSM design parameter inputs with associated units of measure.
2. Trade-off study analysis showing the rationale for the addition of inputs.

Task 2 Development of the Dynamic Ship-Moor Analysis

A. The NSRDC "Ship Motion and Sea Load Computer Program" described in NSRDC Report #3376, the "Second-Order Steady-State Forces and Moments on a Surface Ship in Oblique Regular Waves" by N. Salvenson, February 1974, and the NSRDC drifting force estimate with analytical derivation, will be furnished as Government Furnished Information (GFI) to the contractor as part of this contract. The Contractor shall review and familiarize himself with this material. Also government furnished will be consulting services of NSRDC systems engineer concerning the "Ship Motion and Sea Load Computer Program." These consulting services will include:

1. Clarification of questions that may arise regarding the NSRDC ship motion program including analytical derivation, input requirements, storage requirements, program structure, and error control.
2. Definition of all dimensionless quantities used in the NSRDC ship-motion response computer program.
3. Clarification of the questions that may arise regarding the NSRDC drifting force estimate including its analytical derivations.

B. Modify the existing cable dynamics computer program to accommodate the frequency-dependent loading due to response of a moored ship to the wave.

C. Generate a computer program based on the analysis of ship and moor coupled motion which realistically represents the dynamic response of the selected moor under dynamic loadings. The program shall contain the necessary logics to produce the following information with due consideration of wave induced drifting effects:

1. Response amplitudes and phase lags of various oscillations of a moored ship and buoy.
2. Locus generated by the motion at specific locations of a moored ship.
3. Acceleration at specific locations of a moored ship.
4. Dynamic tensions in hawser lines and mooring legs.

D. Provide a letter report of the results of this Task which includes:

1. A mathematical description of the developed model.
2. A logic flow diagram of the developed coupled dynamic motion model.
3. A source listing of the computer program.
4. An identification of input parameter requirements.

Task 3 Integration of Static and Dynamic Ship-Moor Analysis

A. Integrate the Static Ship-Moor Analysis Program developed in Work Package 1 with the Dynamic Ship-Moor Analysis Program developed in Task 2 of this Work Package. The resultant computer program shall simulate both the static and dynamic responses of a DSSM to loadings induced by winds, currents, external workloads and waves imposed on moored ships.

B. In addition, the program shall contain the necessary logics to produce the following information:

1. Suitability of a moor configuration and its components designed from static loadings to additive dynamic loadings.

Task 3B (cont'd.)

2. Validity of the selected moor in regards to the design rules and the margin of safety.

3. Assessment of the selected moor displacements under the worst operational and survival loading conditions.

4. Prediction of the statistic responses of the selected moor to arbitrary environmental conditions.

C. Provide an interim technical report of the results of this Task which includes:

1. A description of the integrated computer program.

2. A logic flow diagram of the selected moor validation procedure.

Task 4 Computer Program Documentation and Validation

Using FORTRAN IV as the programming language, code and implement the design program of Task 3 on the NSRDC CDC 6700.

A. Program Documentation

Document the design model and generate operating instructions for potential users. The documentation shall provide sufficient information to enable Ocean Facilities Engineers to utilize and modify the program. It has been agreed upon between CHESDIVNAVFACENGCOM and the Contractor that the program documentation will be of the quality and detail of the NSRDC Ship Motion Computer Program Manual (NSRDC Rept. 3376, February 1974). The documentation shall consist of the following:

User's Manual

A user's manual which provides instructions to the engineers who generate the input data and use the output information to accomplish a design task. It should include a definition of the input data and format, the sequence of input (deck set-up including control cards), user restrictions, sample problem, and user diagnostics/error messages with associated corrective action.

Program Maintenance Manual

A program maintenance manual which includes coding information such as flow charts with explanations, program listings, diagnostics, symbol dictionary, and debug information. It also encompasses restrictions such as special input routines, program limitations, maximum array sizes, and minimum memory capability required.

Final Engineering Report

The Contractor shall submit a final engineering report. The Final Engineering Report is to detail all work performed, engineering techniques and rationale employed, results, discussions of applicability and conclusions. It will present the development plan and the history of the development, and will include a general discussion of the theory. In addition, it will discuss the problem areas and needed validation effort. It will include a complete bibliography and will incorporate all deliverables and manuals in appendices, less lengthy printouts which will be furnished upon request. It shall contain the derivation of all algorithms and include associated flow charts. Sample applications and solutions shall be given, as necessary, to validate the algorithms.

This report will be prepared using good quality General Electric engineering documentation standards. The report will be furnished to CHESDIVNAVFACENGCOM in ten copies with a reproducible copy.

B. System Demonstration and Acceptance

Utilizing the NSRDC 6700 computer system and program consulting service provided by CHESDIVNAVFACENGCOM funding, the contractor shall:

(1) Create a program source file.

(2) Create a binary file.

(3) Execute the binary file to demonstrate the program.

(4) Conduct calculations on the CDC 6700 with the DSSM computer program for different mooring configurations agreed upon by CHESDIVNAVFACENGCOM and the Contractor to demonstrate that the program is suitable as an engineering tool for ship-moor analysis. These numerical acceptance tests shall verify the capability of the program to generate credible solutions to a variety of input parameters involving not more than two ships, two mooring configurations, two water depths and three sea states. These acceptance tests shall include:

1. Comparisons of the ship response to regular waves in moored and free floating conditions. The GFI-NSRDC computer program will be used for the unrestrained response which will be compared to the restrained response calculated by the DSSM computer program to evaluate whether the numerical outputs of the developed program are reasonable.

B. System Demonstration and Acceptance (cont'd.)

2. Comparisons between static and dynamic responses to external loads as calculated by the DSSM computer program to ascertain if the numerical results are reasonable.

3. Comparisons of the in-air response calculations for well-defined elastic mechanical systems using established analytical methods and the DSSM Computer Program. (See Note below.)

NOTE: A time-domain and frequency-domain comparison was substituted as described briefly in Section 6.0 and more elaborately in the DSSM-4 Acceptance Report.

WORK PACKAGE THREE: TRANSIENT DYNAMIC ANALYSIS OF CABLE STRUCTURES

Purpose

The purpose of this Work Package is to provide an economical, computerized procedure for solution of transient response of cables, or cable-structures, associated with specified construction operations.

Task 1 - Document a computer program which is capable of sizing cables and buoyancy elements, and which computes the limiting loads necessary for performing the following construction operations in the ocean environment with acceptable risks.

1. Lowering/lifting operations.
2. Towing of objects by ships underway.
3. Deployment/implantment of a cable structure from a ship or a floating construction platform.
4. In-situ operations of a cable structure.

This effort is within the bounds of the existing capability of the SEADYN computer program.

Generate a technical report and a user's manual to provide adequate instructions for an Ocean Facilities Engineer to use the computer program. The user's manual shall contain a comprehensive description of the computer program which includes, but is not limited to, a source listing of the computer program, a mathematical description of the systems modeled, and logic flow charts of the computational sequence.

MILESTONES AND DELIVERABLES SCHEDULE

DSSM COMPUTER SIMULATION PROGRAM

ITEM NO.	DESCRIPTION	COMPLETION DATE (Months after Go-Ahead)
(1)	Development Plan Outline & Logic Diagram (Ref. Scope)	One Month
	WP-1: STATIC-LOAD SHIP-MOOR COMPUTER ANALYSIS PROGRAM	
(2)	TASK 1, Letter Report	1.5 Months
(3)	TASK 2, Letter Report	2.5 Months
(4)	TASK 3, Letter Report	3.0 Months
(5)	TASK 4, Letter Report	3.5 Months
	WP-2: DYNAMIC-LOAD SHIP-MOOR COMPUTER ANALYSIS PROGRAM	
(6)	TASK 1, Letter Report	7.0 Months
(7)	TASK 2, Letter Report	7.0 Months
(8)	TASK 3, INTERIM REPORT	9.0 Months
	TASK 4, Computer Program Documentation and Acceptance	
(9)	Acceptance Report (with Source File, Binary File, Execution Results and Calculations)	10 Months
(10)	Users Manual	11 Months
(11)	Program Maintenance Manual	11 Months
(12)	Final Engineering Report	11 Months
	WP-3: TRANSIENT DYNAMIC ANALYSIS OF CABLE STRUCTURES	
(13)	TASK 1, Technical Report and User's Manual	8.5 Months

APPENDIX B

LETTER REPORTS 1-9

LETTER REPORT No. 1

A PLAN FOR THE DEVELOPMENT OF A DEEP SEA
SHIP-MOOR COMPUTER SIMULATION PROGRAM

CONTRACT NUMBER N62477-76-C-0002

By: R.L. Webster

6 November 1975

ELECTRONIC SYSTEMS DIVISION
THE GENERAL ELECTRIC COMPANY
SYRACUSE, NEW YORK

This Letter Report is submitted in compliance with item no. (1) of the Milestones and Deliverables Schedule of Contract N62477-76-C-0002, dated 17 June 1975 as revised 4 August 1975.

CONTENTS

INTRODUCTION

The principle objective of this contract effort is to provide a computer program capable of analyzing the performance of a Deep Sea Ship Moor (DSSM) exposed to various environmental and functional conditions. This effort is to be viewed as interim in nature in that it merges existing technologies into a convenient tool and does not undertake significant developmental improvements. In addition to providing a tool which will relieve the design engineer of a significant amount of computational burden, this effort is intended to demonstrate the feasibility of the general approaches taken and identify limitations and areas where further effort would be most productive.

The computer program development has been divided into three work packages. These are summarized below:

Work Package 1 - Static Analysis

1. Determine the steady-state configuration of a ship and mooring system subjected to wind, ocean currents, and workloads.
2. Evaluate the performance of the moor relative to a set of specified design criteria.
3. Size the mooring system components in accordance with selected materials, configuration, functional requirements and design rules.

Work Package 2 - Dynamic Analysis

1. Estimate the dynamic effects of arbitrary sea states. This will include adjustments in the steady-state position due to wave induced drift forces.
2. Integrate the results of Work Package 1 and document and demonstrate the combined program.

<u>Work Package 3 - Transient Dynamic Analysis</u>

1. Package and document an existing program (SEADYN) which deals with the transient dynamic response of underwater cable systems.

The combination of the first two work packages represents what will be called the DSSM computer program. It will provide extensive computational support to the mooring design engineer. The DSSM Program will solve static responses using iterative nonlinear methods. This is required because the mooring system will generally be nonlinear due to large displacements. The dynamic solutions will assume a small oscillatory motion about a quasi-static reference configuration and both the ship and mooring system equations will be linearized. Responses to arbitrary sea states will be estimated by superimposing the responses to a system of regular waves.

The DSSM Program will be a significant improvement over existing computer simulations in three major aspects. First, it integrates a static and dynamic solution which allows much more generality and flexibility. Second, it includes the full six degrees of freedom of ship motion. Finally, it includes the dynamic effects of the moor (including mass and damping) rather than simply adding elastic restoring forces to the ship's equations. This last feature is significant to the mooring designer who is concerned about the dynamic responses of the mooring components.

The transient cable response program, SEADYN, will be a useful adjunct to the DSSM Program. Since it is a nonlinear time domain program it allows detailed investigation of cable behavior that cannot be dealt with in the linearized frequency domain where the DSSM Program will operate.

A number of reports and papers were reviewed in the preparation of this development plan. A partial list which includes the more significant ones will be found at the end of this report. Two of the references [1-2] discussed the dynamics of moored ships in response to waves. In each of these the dynamic characteristics of the moor were neglected and simple relations for elastic restoring forces were added to the motion equations for the ship. In reference 1 the effects of wave induced drift forces were treated but the effects of wind and current were ignored. Only the effects of an imposed harmonic load were treated in Reference 2. Reference 3 deals with the determination of elastic restoring forces based on the well-known catenary equation and is considered to be inadequate for the general requirements of this effort. References 4 and 5 deal primarily with static loading on ships due to wind and current and will be quite useful in Work Package 1. Reference 4 also contains a computer program for estimating dynamic response to variable winds and steady currents which will not be used in this effort.

The following discussion presents some of the important aspects of the effort and outlines the approach to be followed in the development of each work package. Logic flow charts which give an overview of the static and dynamic portions of the DSSM Program are given at the end of the DISCUSSION Section. Finally, the schedule used in planning this effort is given along with the dates when the deliverables are due (contractual requirements). Detailed descriptions of the techniques employed and the specific nature of the DSSM Program will be given in the course of this effort by means of these scheduled Letter Reports.

DISCUSSION

The DSSM computer program will evaluate the combined effects of wind, currents, workloads and surface waves under the assumption that the dynamic part of the response is induced only by the surface waves acting on the ship and any surface buoy associated with the mooring system. This dynamic response will be treated as a small perturbation on the state induced by the steady components of wind, current and work loads with adjustments being made to account for the wave induced drift forces. The dynamic response to irregular waves (arbitrary sea state) will be assumed to be a linear superposition of the responses to a set of regular waves which will be selected by the user. Thus established techniques for random response analysis will be utilized in the dynamic calculations.

The static response calculations, however, must deal with the nonlinear responses of the system. These nonlinearities come primarily from the geometric and material nonlinearities of the mooring components and the position dependent nature of the wind and current loadings. Since the dynamic response is defined relative to a static reference state, a nonlinear static analysis is an important part of the DSSM Program. Aside from its utility to the dynamic analysis, the static analysis can be used as an effective design aid. Thus the static analysis serves the dual functions of helping the designer select a suitable candidate for dynamic analysis and then provides the reference state for the dynamic perturbations.

It is not intended that the developments under this contract result in a fully automated design tool. The interim nature of this work suggests that it is more appropriate to provide computational aids to the designer/user and leave the judgemental functions to him. Thus the DSSM Program will be developed in a segmented form. In the first segment of operation the user will stipulate

static design requirements and postulate a mooring system. The static portion of the DSSM Program will then evaluate the moor against the design requirements for a given ship in a given set of environmental and work load conditions. In the event the postulated moor does not meet the requirements a message stating where the deficiency is will be given. It would then be left to the user to modify the moor and re-initiate the analysis. Given that the basic requirements were satisfied, the program would then proceed to select mooring component details using predetermined design rules and a "catalog" of available components. Failing in this, the program would identify the deficiency and the user would be required to input a modified moor. This sequence would be repeated until an adequate moor was obtained.

During this stage of operation some estimate of the ship's restoring forces are required. Three options present themselves. The first is to assume that the ship is fixed in heave, pitch and roll and free to move in surge, sway and yaw. This amounts to saying the restoring forces are large compared to mooring forces and work loads. Second, is the use of the restoring forces obtained for the ship in the NSRDC Program [6] (see the discussion which follows), and the third option is the input of these coefficients. Each of these options will be considered during the development.

Once a satisfactory design is obtained, the next stage of operation requires the specification of a particular wind and current (heading, magnitude and distribution) and a set of static work loads (if any). The static configuration of the system under these loads becomes the reference state for the dynamic response calculations. The DSSM Program will then generate the linearized transfer function for the mooring subsystem and the harmonic forcing functions

representing a set of regular waves acting on any surface buoys. In an independent operation the linearized parameters for the ship will be determined for the same set of regular waves. The ship data will be generated by the NSRDC ship's motion program [6] and stored on an auxiliary storage device. This data will include a set of tables identifying the effect of roll amplitude on roll damping for the various conditions. (This portion of the effort is GFI.)

The DSSM Program will then assemble the transfer functions from the moor and ship and solve for the responses to the regular waves. The solution for the response to each wave will be done iteratively to adjust for roll damping effects and the change in static position due to the wave induced drift forces. These wave induced drift forces will be determined using a subprogram developed by NSRDC (GFI).

The final stage of the analysis begins with the specification of a sea spectrum and proceeds to superimpose the regular wave effects. The response estimates are then compared to specified design limits. This final stage can be repeated for as many spectra as desired without returning to the previous stages as long as the wind, current and work loads do not change. Naturally, the previous stage can be repeated whenever a change is desired in static loads. Should these procedures identify a deficiency in the mooring system, it would be left to the user to modify the moor and repeat the cycle.

Two macro-flow charts are presented at the end of this discussion which summarize the functions of the DSSM Program. The major developments and activities anticipated for each of the work packages are outlined below.

Work Package 1 - Static Analysis

a. Formulate static wind and current loading models for ships and surface buoys. Three basic options are being considered for ship loading:

   1. Equivalent ship selection and scaling using the DM-26 approach. Only the EC-2 and DD-692 models will be available for selection. Two variations of this option may be possible: automatic selection based on ship parameters or user selection.

   2. Input a table of loading functions. This may include a user generated catalog.

   3. Use a set of approximate analytical functions similar to those of References 3 and 7.

b. Modify the SEADYN program to include a ship element for static analysis.

c. Modify the SEADYN program to evaluate the watch circle.

d. Develop mooring component selection schemes and moor performance evaluation. (Use DM-26 and additional GFI data.)

COMMENTS

The basic static analysis techniques in SEADYN will be utilized. It is not clear at this point whether SEADYN will be integrated with the DSSM Program or if portions of SEADYN will be extracted and included in the DSSM Program.

Work Package 2 - Dynamic Analysis

a. Obtain ship's transfer function and harmonic load vectors from NSRDC program. Coordinate with NSRDC on the format of the stored data.

b. Develop buoy transfer function and loading vectors.

c. Modify SEADYN to generate combined buoy and cable transfer functions and load vectors.

d. Write subroutines for assembling equations and solving for regular wave responses. Coordinate with NSRDC on drift force subroutine.

e. Write regular wave superposition and performance evaluation routines.

f. Detailed checkout and documentation. Coordinate with CHESDIV on selection of demonstration problem(s).

g. System demonstration at NSRDC.

COMMENTS

Most of the program development and checkout will be done in Syracuse on the Honeywell system. The transferral to and the demonstration on the NSRDC CDC6700 system will be facilitated by a remote access from Syracuse. The existing Honeywell and GE equipment are not convenient for a remote interface; however, some special purpose equipment will be available prior to the anticipated need. Details on the equipment will be provided to NSRDC later.

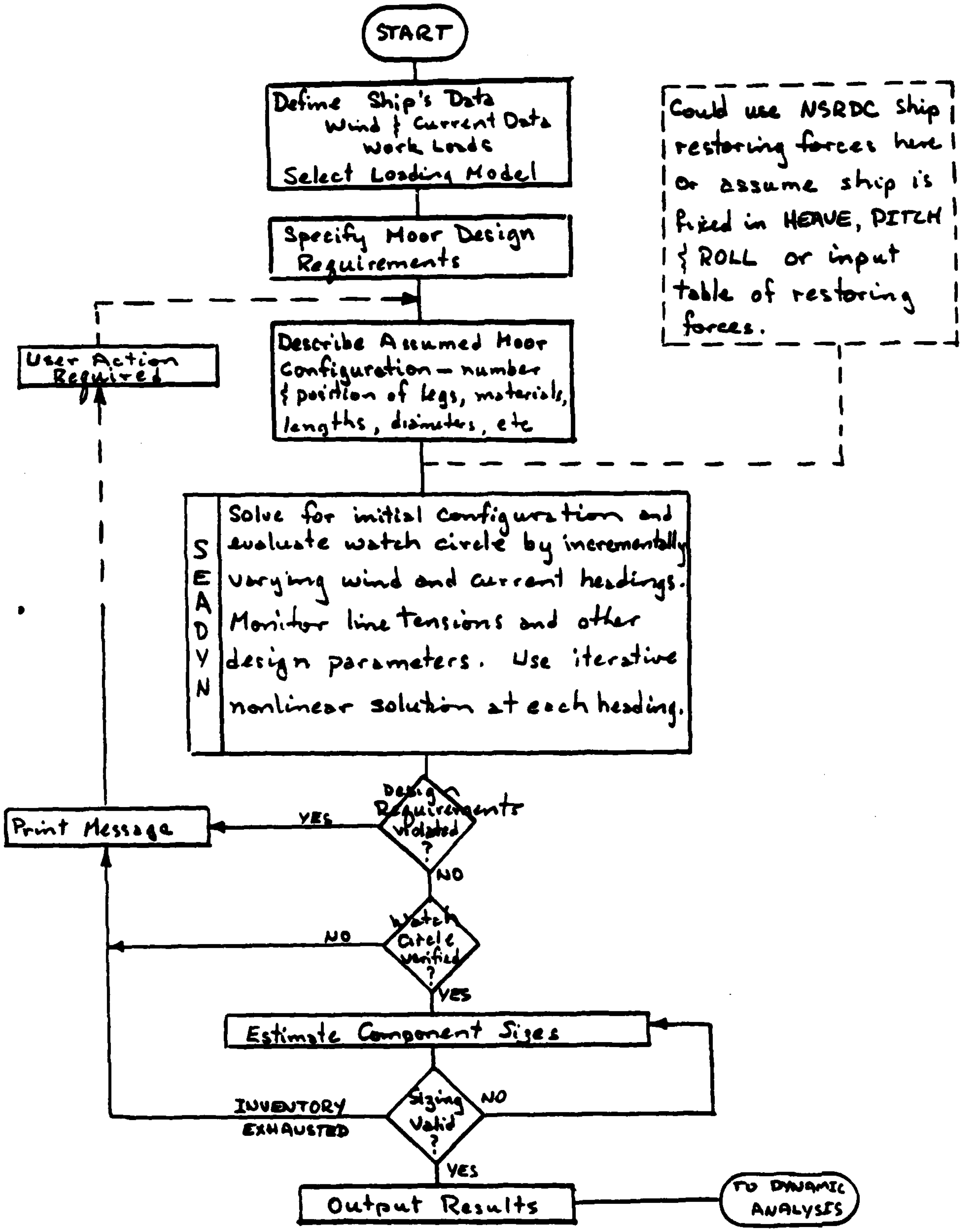
Work Package 3 - Transient Dynamic Analysis

The present version of the SEADYN program plus any modifications required for the DSSM Program will be documented and an operating version of the program will be delivered.

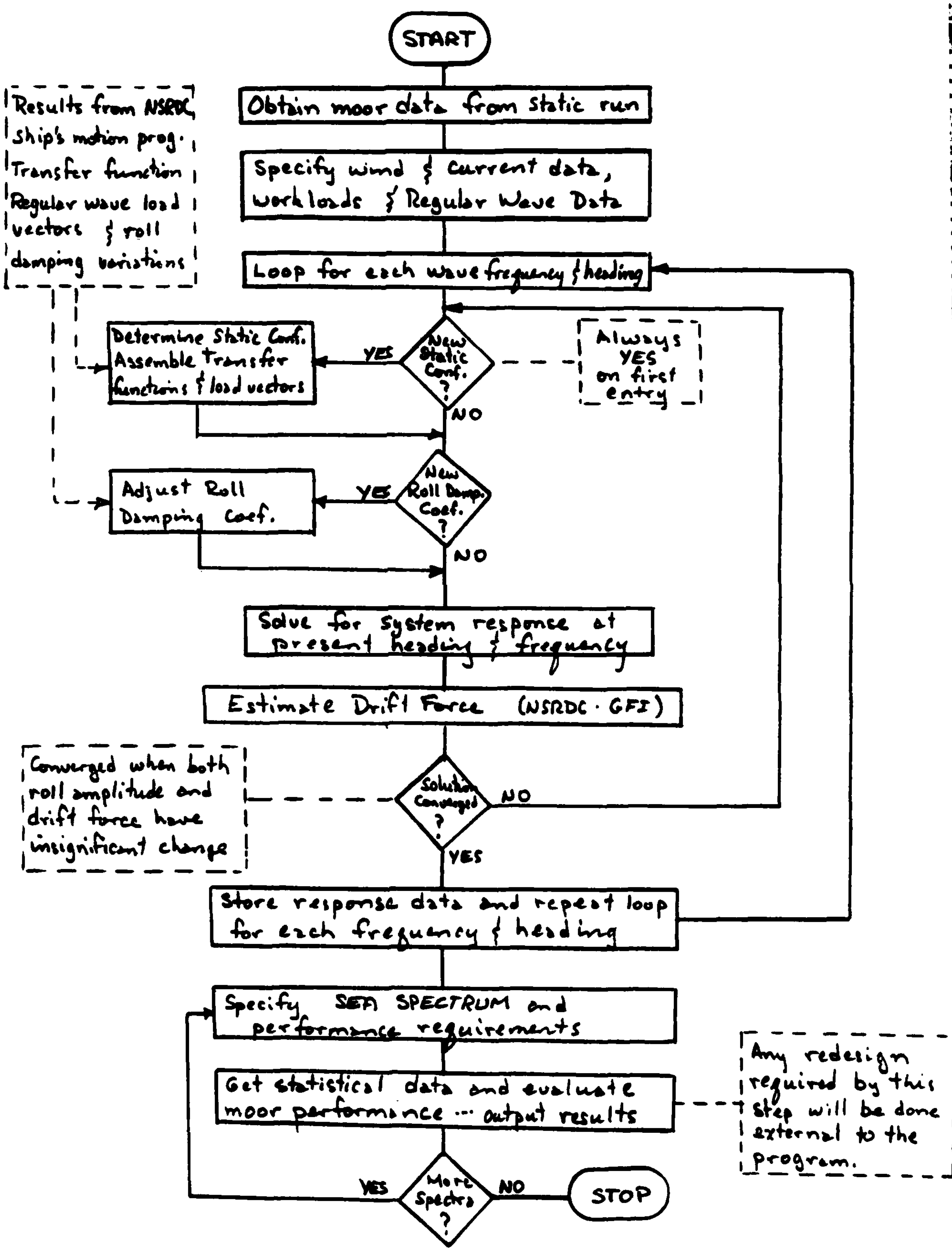
The schedule shown following the logic flow charts details the sequence of events in this effort. The principle investigator in this contract is R.L. Webster. The development plan effort began with final signing of the contract on 7 October 1975. R.L. Webster and Dr. Y.H. Chey contributed to this activity. The planning also involves Dr. Chey in the analytical and trade-off studies of the first two work packages. The computer programming and checkout will be done primarily by R.L. Webster. He will be assisted in the programming and documentation work by Mr. J. Klein. Computer program validation and demonstration activities are scheduled to begin in mid-June at NSRDC. Mr. Webster will travel to NSRDC for that activity.

The dates for submitting the deliverables on this contract are indicated on the schedule sheet and on the page immediately following it.

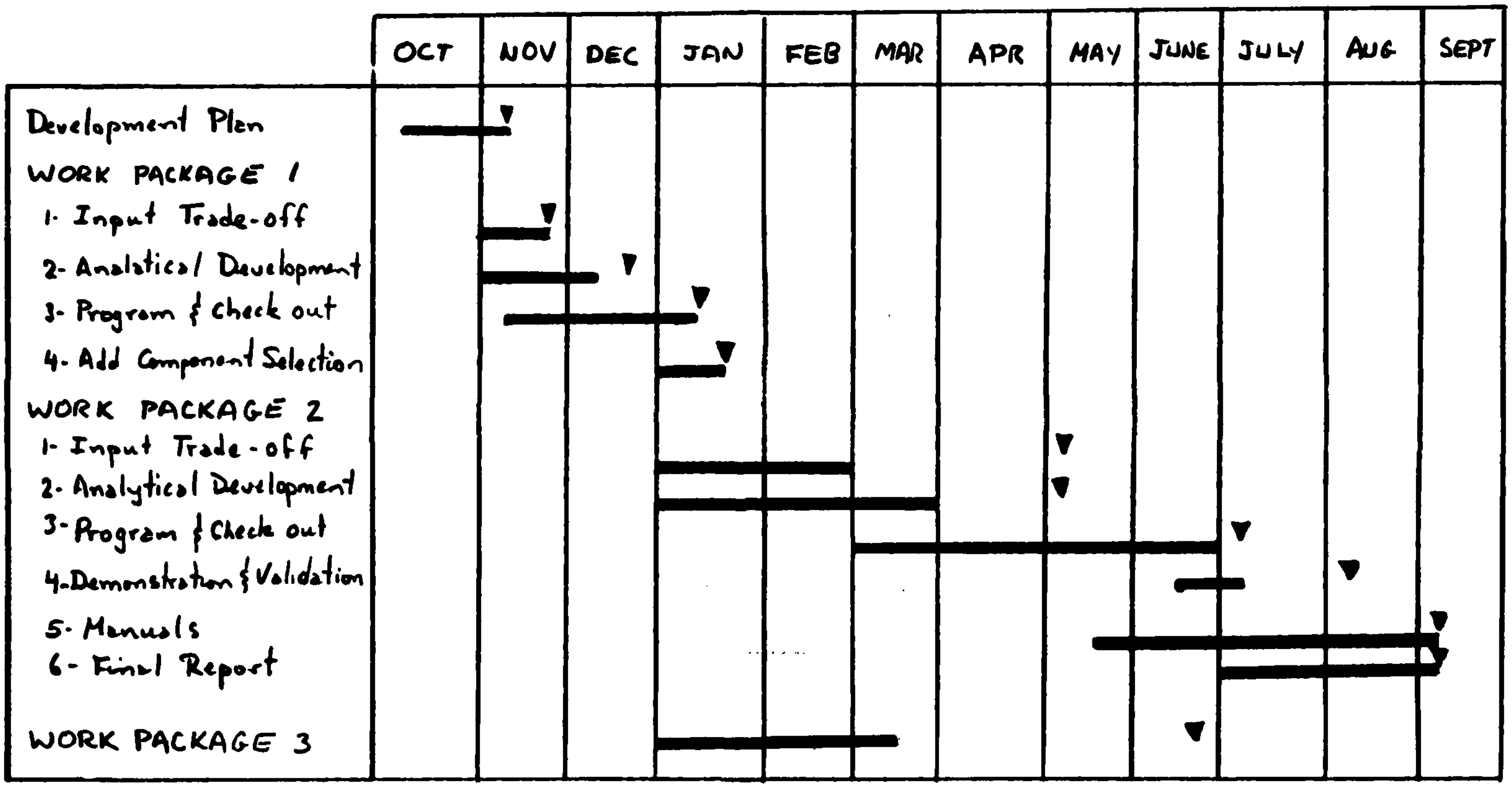
DSSM STATIC ANALYSIS



DSSM DYNAMIC ANALYSIS



DSSM DEVELOPMENT SCHEDULE



▼ Deliverables Due

MILESTONES AND DELIVERABLES SCHEDULE

START DATE: 7 October 1975

		Contract Schedule	Date
1.	Development Plan (plan outline and logic diagram)	1 month	7 November 1975
2.	Static Analysis Input Trade-Off	1.5	21 November 1975
3.	Static Analysis Math Model	2.5	22 December 1975
4.	Static Analysis Computer Implementation	3.0	7 January 1976
5.	Static Analysis Component Selection	3.5	21 January 1976
6.	Dynamic Analysis Input Trade-off	7.0	7 May 1976
7.	Dynamic Analysis Math Model	7.0	7 May 1976
8.	DSSM Integrated Program *INTERIM REPORT*	9.0	7 July 1976
9.	Acceptance Report	10.0	7 August 1976
10.	User's Manual	11.0	7 September 1976
11.	Programmer's Maintenance Manual	11.0	7 September 1976
12.	Final Report	11.0	7 September 1976
13.	SEADYN Manual	8.5	21 June 1976

REFERENCES

1. Zarnick, E.E., Casarella, J.J., "The Dynamics of a Ship Moored by a Cable System Under Sea State Excitation," Dept. of Civil and Mech. Eng., Catholic University of America, Washington, D.C., Report 72-5, July 1972 (AD 746490)

2. Muga, B.J., Wilson, J.F., DYNAMIC ANALYSIS OF OCEAN STRUCTURES, Plenum Press, N.Y., 1970.

3. Altman, R., "Forces on Ships Moored in Protected Waters," Hydronautics, Inc., Tech Report 7096-1, July 1971.

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LETTER REPORT NO. 2

DEFINITION OF DESIGN-PARAMETER INPUTS
(WORK PACKAGE 1, TASK 1)

CONTRACT NUMBER N62477-76-C-0002

By: R. L. Webster

20 November 1975

ELECTRONIC SYSTEMS DIVISION
THE GENERAL ELECTRIC COMPANY
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This Letter Report is submitted in compliance with item no. (2) of the Milestones and Deliverables Schedule of Contract N62477-76-C-0002, dated 17 June 1975 as revised 4 August 1975.

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INTRODUCTION

The static analysis portion of the DSSM Computer Program has as its objectives the following:

1. Determine the steady-state configuration of a ship and mooring system subjected to wind, ocean currents, and work loads.
2. Evaluate the performance of the moor relative to a set of specified design criteria.
3. Size the mooring system components in accordance with selected materials, configuration, functional requirements, and design rules.
4. Provide a starting configuration for dynamic analysis.

The purpose of this report is to summarize the results of a study of the input required to meet those objectives. In addition, some clarification to the static analysis procedures described in the Development Plan (Letter Report No. 1) will be given.

DISCUSSION

Five categories of input data will be treated in this discussion. They are:

1. Design Constraints
2. Environmental Conditions
3. Ship Geometry
4. External Loading (Work Loads)
5. Moor Component Characteristics

Input is required in each of these categories. Although there is some overlapping in the use of the data (e.g., environmental loads are intimately associated with ship geometry) each of these categories will be addressed separately below. A chart listing the important inputs is presented at the end of the discussion in Table I.

Design Constraints

The static analysis is formulated to assist the designer evaluate a selected moor against the following requirements:

1. Watch Circle - the vessel shall remain within a circle of given radius under the combined action of specified wind, currents and work loads. This assumes the winds and currents may change direction significantly while the ship is moored.

2. Mooring Component Strength - None of the mooring lines, attachments, anchors, etc., shall be loaded beyond a specified design limit load. This design limit load represents the ultimate capacity of the component divided by a factor-of-safety and other factors intended to adjust for dynamic and other effects.

3. Anchor/Mooring Line Interface - The holding power of an anchor is a function of the direction of the mooring line force acting on it. The angle between the mooring line and the bottom at the anchor is therefore limited to be within some specified value.

The last two requirements apply to the system under operational and survival conditions. Depending on the purpose of the moor the watch circle requirement may or may not apply in the survival condition. Operational and survival conditions would generally be treated as two separate situations and separate computer runs made to evaluate them. This would mean specifying two different sets of environmental conditions and possibly somewhat different configurations (perhaps no working lines would be overboard in the survival state). In situations where the watch circle is a constraint on the operational conditions only, it may be more economical to by-pass the watch circle constraint in the survival analysis.

The following appear to be a reasonable set of input parameters for the design constraints:

1. Watch circle radius.

2. Design safety factor for component strengths.

3. Design load factor to account for other effects not accounted for in the specified loading (e.g., dynamics).

4. Anchor attachment angle.

The specification of an additional load factor which represents the survival condition was considered and then eliminated. Its use would imply a nearly linear relationship between the external loads and the internal loads. Such a linearity generally does not exist with mooring systems due to the geometric nonlinearity (large displacements) associated with the mooring lines and the position dependent loading characteristics of both the vessel and the lines.

An additional set of design constraints will be implied by the procedure used for component selection. Only standard size components will be used. Thus a catalog of available components will be established and the appropriate components will be selected from the catalog. The user of the computer program will be able to create or update the catalogs on an "as needed" basis. The details of the component selection procedure will be worked out in Task 4 of Work Package 1.

Environmental Conditions

The environmental conditions of importance to the static portion of the DSSM development are:

1. Wind - magnitude, direction and vertical distribution
2. Current (surface and subsurface) - magnitude, direction, and distribution
3. Site description - water depth, bottom topology and constituents, fluid specific weight and viscosity.

Specifically omitted from the static analysis are the effects of waves on the system.

A great deal of complexity can be introduced when one attempts to describe realistic spatial and temporal variations of wind and current. In general these factors can vary greatly over the period the ship is in the moor as well as being very dependent on the site of the moor. Further complicating matters is the fact that there is usually not a direct relationship between the wind and current, and they may vary independently. Also, the surface currents may be nearly independent of the subsurface flow.

DM-26 simplifies the problem by presuming the subsurface currents have no effect on the ship and that the maximum surface current and wind loading occur simultaneously. The vertical distribution of the wind is ignored and the interaction with the moor is neglected. This assumes that one is able to identify what the maximum conditions are and superimpose them. Such a procedure is appropriate for estimating the maximum possible loads on a ship but it does not adequately address what is happening to the moor in multi-point moor situations, nor does it address the watch circle determination.

One approach to evaluating the moor interaction and the watch circle is to assume that the maximum combined ship loading (side force, end force and yaw moment from DM-26 for example) is applied and then the side and end forces are incrementally rotated without regard for the ship orientation until the watch circle is defined. This should give an upper bound for the watch circle but there may be no point on that circle which represents an actual configuration of the system for the given conditions.

At the other end of the spectrum is an iterative solution which incrementally varies the wind, and currents in some logical pattern and solves for the actual response of the system to the combined effects. This approach recognizes that as the loads are applied the ship and the mooring components will change their orientation with respect to the flows and thus alter the total load applied. It represents a massive amount of computation for the general case of independently variable wind and currents. As an example of the extremes that such an approach could go, assume that the subsurface and surface currents and the wind vary independently. After selecting a specific number, n, of headings relative to a fixed reference frame, the analysis would proceed with the evaluation of n^3 static configurations to determine the envelopes for the watch circle and the component loads. Assuming that ten directions were evaluated this would mean that 1000 static solutions would be required. The number of solutions could be reduced by using an optimization procedure which searched for the upper limits rather than evaluating all of the points in the solution space. This would lead to further complications in the analytical and programming development which do not seem justifiable at this point.

The first procedure eliminates one of the loops in the evaluation and thus cuts the number of static solutions by a factor of n. Furthermore, it reduces the amount of computation in each solution since the loads are assumed to have a fixed orientation. After the direction of maximum loading on the moor is obtained and the components sized, it would be necessary to attempt to get a correlation with a set of wind and current data and perform a fully nonlinear static solution to get a starting reference state for the dynamic analysis. This is the procedure implied in Figure 1 and the Development Plan.

The basic environmental input required to estimate the ship loading using the empirical loading functions after the manner of DM-26 are:

1. Magnitude of design wind velocity and surface current plus the number and spacing of the headings to be evaluated.

2. Water depth (average value for sloped bottom)

Additional site related information is required. The important parameters are:

1. The location of the anchor points relative to a fixed Cartesian reference frame.

2. A specification of the ground condition at each anchor. This could be a holding power factor or a mnemonic which signals what factor to use.

3. The magnitude and distribution of the subsurface current plus the number and spacing for the headings to be evaluated.

Optional input to allow the specific selection of a magnitude and direction for the wind and current will also be provided.

In addition to the loading function approach of DM-26, the static solution will allow the selection of a set of analytical functions to evaluate the ship loading. These functions will consider a variation of the wind velocity in the vertical direction. Thus input for this distribution will also be provided for.

Ship Geometry

Under the category of ship geometry data are parameters which describe the physical characteristics of the ship as well as identify the loading functions to be used. In addition to being used in the determination of the values of the ships loading, the physical description may be used to identify ship similarities in an effort to select a representative set of loading functions from a catalog.

The minimum number of input parameters for a ship appears to be that required to specify a set of loading functions and perform the scaling after the manner of DM-26. These parameters are:

1. A set of points representing the end forces, side forces and yaw moments for wind and surface currents of various magnitudes and headings.

2. The following parameters describing the test ship used to obtain the loading curves in (1):

   Length for wind load, L_t
   Side projected area above water line, A_{ts}
   End projected area above water line, A_{te}
   Wind Force coefficient, C_f
   Wind moment coefficient, C_m
   Length at water line, L_{tw}
   Test Water depth, h_t
   Displacement, Δ_t
   Propeller projected area, A_t

3. A set of parameters describing the vessel being analyzed (may be omitted if the ship being analyzed is the same as the test ship in (2))

   Length for wind load, L
   Side projected area above water line, As
   End projected area above water line, Ae
   Length at water line, L_W
   Displacement, Δ
   Propeller Projected area, A

Data for items (1) and (2) can be placed on a catalog and simply selected at the analysis time by specifying the catalog number or they can be input with the run. When the ship being analyzed has the same geometric data as the one described in items (1) and (2) then item (3) need not be input.

In some situations it may be desirable to have the program select the appropriate curves from the catalog. In this case items (1) and (2) would be omitted and item (3) would be augmented by some additional data. The catalog would also have to contain corresponding data for the test ship. The details of this ship selection process have not yet been fully defined but it appears that the following parameters would be meaningful:

Beam and Draft dimensions
Projected areas for end and side below water line
Locations of the centers of pressure below and above the water line
Cross-sectional area of hull at midships
Location of ship's center of gravity

A third option that will be provided for obtaining the ship's loading involves the use of analytical functions rather than the curves discussed above. These functions will be described in detail in the next letter report. They will allow for more detailed treatment of the wind loading and may require more description of the structure above the water line. Thus the projected areas could be subdivided to represent various super structures and the above water portion of the hull. Each of the subdivisions would require the specification of the end and side projected areas and an estimate of the location of the center of pressure relative to the ship's center of gravity.

The inclusion of the effects of the mooring and working load forces on the ship requires the specification of the location of each of the attachment points relative to the ship's c.g.

External Loading (Work Loads)

It is assumed that the ship may be loaded by various lines and weights overboard. These can either be treated as specific point loads on the ship or by defining the line and supported loads. In some cases the working line may appear simply as another mooring leg while in others the payload would be suspended above the bottom. Input for the working lines will follow the basic approach used in SEADYN. Since it is not significantly different from the mooring line description no further discussion will be given here.

Mooring Component Characteristics

The general configuration of the mooring system will be described through input. The pertinent data are the unstretched lengths of the lines, the modulus of elasticity (or a set of values for nonlinear materials), the material density, the ultimate strength, an estimate of the drag diameter and the load bearing area, a drag coefficient selector, a specification of the number of elements used to represent each segment of the lines, and an indication of whether the segment is in the water or above it (e.g., hawser lines from the ship to a riser buoy). Also required is the specification of the topology of the system (i.e., how the lines are connected from ship to anchor and where in the lines are the buoys, sinkers or other lumped bodies). The description of the topology will follow the methods used in the SEADYN Program in that the lines will be represented by a set of straight elements between a set of nodes. The buoys, anchors, etc., will be located at the nodes.

The most readily implemented form of input for the mooring system is to use the SEADYN Program with only minor modifications to accept the ship data. SEADYN presently requires an estimate of the static configuration of the system in order to start the analysis. It seems more desirable to specify only the anchor locations and the location of the ship's c.g. relative to some fixed Cartesian reference frame and use the catenary equations and the system topology data to estimate a starting configuration. The catenary equations could also be used to estimate the load bearing areas of the lines by locating the ship at various points on the desired watch circle and estimating the peak tensions. These features require further development beyond the present capability of SEADYN but should be feasible to implement.

The following then represents a reasonable set of input parameters for the mooring lines:

(1) A list (catalog) of the possible material data which will include modulus of elasticity, ultimate strength and material density data plus a bulk factor which will be used to estimate the drag diameter once the load bearing area is selected. Thus if the load bearing area represented a net diameter of d, then the bulk factor times d would be used for drag load calculations.

(2) A list identifying the line segments. Each segment will define:

a) the nodes at the beginning and end of the segment
b) the material used (reference to the catalog)
c) the initial (unstretched) length
d) the number of elements representing the segment
e) a drag coefficient selector which can also be used to signal when the segment is not under water
f) a signal to identify any component selection requirements.

(3) A list of all of the buoys, sinkers, etc. indicating at which node they are attached and estimating their weight and drag diameter. Also a signal will be provided to identify any component selection requirements. Thus the type of buoy or anchor will be identified.

(4) The coordinates of the ship c.g. relative to a fixed Cartesian reference frame. This requires specification of orientation as well as position. Since pitch and roll will be assumed to be zero and the reference frame will be chosen to have one of it axes in the direction of gravity this will require 4 coordinates.

(5) A specification of the number of points on the theoretical watch circle to be checked in estimating the load bearing areas of the mooring legs.

As an auxiliary to the mooring component descriptions, a means will be provided to set up a catalog of each of the available components as contained in DM-26. Additional components can be added or existing ones modified. The specific form of these catalogs will be developed in Task 4 of work package 1.

Units of Measure

Due to the general nature of a computer program of this type and the slow but relentless movement towards the adoption of the metric system it is felt advisable that the program be written without any implied conversion factors and that all dimensional data be input in a consistent set of units. Thus the user of the program would be required to establish a single set of units involving length, force, mass and time and use that system uniformly throughout. This would mean, for example, that if linear dimensions are given in feet, then areas would be given in square feet and if the force unit was chosen to be pounds, then the modulus of elasticity would be in pounds per square foot. Conversion between mass and weight would then require the input of the magnitude of gravitational acceleration in consistent units. In the example above this would be ft/sec^2 and mass would then have the units of $lb\text{-}sec^2/ft$.

Comments on the Static Analysis Procedure

The foregoing discussions and the Development Plan have given some outline of the complexity of the static analysis problem. Precise treatment of the effects of the interaction between the ship and the moor which includes the nonlinear and position dependent effects can be a costly process. However, it is felt that some precision beyond that implied in DM-26 is needed. The outlined procedures for the design evaluations represent a compromise between crude approximations and costly iterative solutions. Assuming that maximum ship loads can be applied at the ship's c.g. and rotated without regard to the ship orientation results in a signficant reduction in computational effort required to evaluate the watch circle.

The SEADYN static solution procedures make it possible to generalize the configurations of the mooring system and working lines. There will be no restriction on the number or location of the attachments to the ship other than a limit implied by storage dimensions. It is also possible to generalize the assumptions about the static response of the ship in the moor. The usual assumption is that under the static loading the heave, roll and pitch displacements are negligible and thus are treated as zero (i.e., fixed). This leaves the ship free to move anywhere on the calm sea surface in order to balance the applied loads and the mooring forces, but it is constrained from moving out of the plane. This out-of-plane constraint can be relaxed

if hydrostatic restoring forces are specified in the heave, roll and pitch directions. These restoring forces could be input for the ship or it would be possible to obtain them from the data stored by the NSRDC program. Inclusion of these out-of-plane restoring forces represents a minor extension of the solution procedure and can be implemented very readily.

Once the mooring components have been selected and the static design requirements satisfied, the static analysis will be used to generate the reference configuration for the dynamic analysis. At this point a specific combination of wind and current loads in a particular direction are used to move the system to the reference state. In this operation full account is taken of the position dependent nature of the ship's loading. Thus the reference state represents an actual equilibrium configuration which balances the external wind and current loads with the mooring and working line loads.

Figure 1 is a modified version of the macro-flow chart for the static analysis that was presented in the development plan. This modification reflects the optional branch to estimate load bearing areas for the mooring lines. This branch would be used only when the area data was not specified in the input.

AD-A163 511 DEEP SEA SHIP MOOR VOLUME 5(U) GENERAL ELECTRIC CO SYRACUSE NY ELECTRONIC SYSTEMS DIV SEP 78 CHES/NAVFAC-FPO-1-78(16)-5 N62477-76-C-0082 2/3

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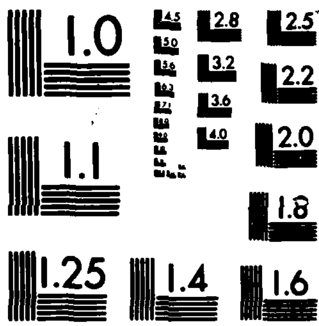

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

TABLE I

SUMMARY OF DESIGN-INPUT PARAMETERS

1. Design Constraints

   a - Watch Circle Radius

   b - Component Factors-of-Safety

   c - Component Load Factors

   d - Anchor Attachment Angles

   e - Available Component Tables

2. Environmental Conditions

   a - Magnitude of design wind velocity and surface current plus the number and spacing of the headings to be evaluated.

   b - Water depth (may be implied by locations of anchors and ship)

   c - Location of anchor points

   d - Description of ground type at each anchor

   e - Subsurface current magnitude and distribution plus the number and spacing for the headings to be evaluated

   f - Fluid density and viscosity

   g - Vertical distribution of wind velocity (optional)

   h - Selectors for wind and current loading model

3. Ship Geometry

   a - Tables of loading functions for end and side forces and yaw moment for wind and surface currents of various magnitudes and headings (may be given in a catalog or input with the run).

   b - DM-26 parameters for test ship (see discussion)

   c - DM-26 parameters for design ship (see discussion) (may be omitted if same as test ship.)

   d - Additional ship descriptors (see discussion) which may be required for equivalent ship selection or the use of the analytical loading model

TABLE I (CONT)

SUMMARY OF DESIGN-INPUT PARAMETERS

4. External Loading (Work Loads)

   a - Location, orientation and magnitude of any point loads

   b - Description of working lines and payloads including stiffnesses, weights, diameters, drag data, configuration, etc.

5. Mooring Component Characteristics

   a - Catalog of material data

      Modulus of Elasticity (table for nonlinear materials)
      Density
      Ultimate Strength
      Bulk Factor (to estimate drag diameter)

   b - Line Segment data

      Nodes at beginning and end
      Material reference
      Load bearing diameter (optional)
      Initial Length
      Number of elements to be used to represent segment
      Drag coefficient selector (zero means not underwater)
      Component Selection Signal

   c - Buoy, Anchor, Sinker List

      Body identification
      Node where body attached
      Estimated weight
      Estimate drag diameter (not required for anchors)
      Component Selector Signal

   d - Estimated Location of Ship's c.g. in unloaded state

   e - Number of points to be checked on theoretical watch circle when estimating leg sizes

   f - Catalog of available components

      Anchors - type, weight, holding power factors
      Buoys - type, weight, diameter, height
      Sinkers - weight, size
      Chain - type, weight, drag data, strength
      Ropes - type, weight, diameter, strength

DSSM STATIC ANALYSIS

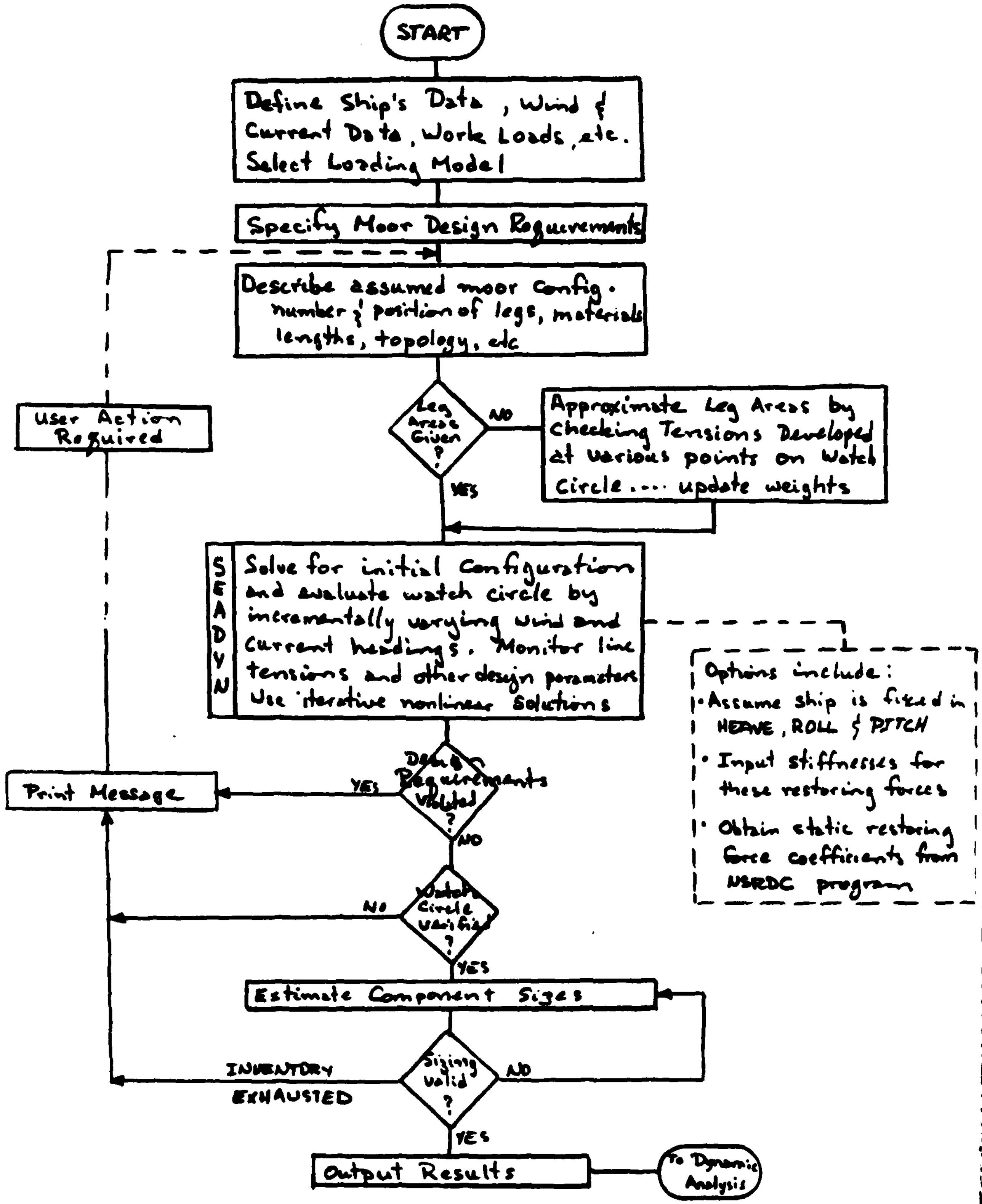

Figure 1 Revised Static Analysis Macro-Flow Chart

LETTER REPORT NO. 3

DEVELOPMENT OF THE STATIC SHIP LOADING ANALYSIS
(WORK PACKAGE 1, TASK 2)

CONTRACT NUMBER N62477-76-C-0002

By: R. L. Webster

19 December 1975

Electronics Systems Division
The General Electric Company
Syracuse, New York

This Letter Report is submitted in compliance with item no. (3) of the Milestones and Deliverables Schedule of Contract N62477-76-C-002, dated 17 June 1975 as revised 4 August 1975.

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INTRODUCTION

This Letter Report details the procedures to be used in the determination of the steady-state loads acting on a moored ship. The forces considered are the longitudinal and transverse forces and yaw moments due to winds and surface currents. Chapters 5-7 of NAVFAC Design Manual 26 were used as the primary reference for this effort. The DM-26 approach utilizes experimental curves for the forces and moments for various headings of wind and current for a set of "representative" vessels. Similarity scaling is then applied to get loading values for ships other than those tested. The following discussion describes the approach that will be used in implementing the DM-26 procedures.

The DSSM static analysis will also provide an optional representation for the forces and moments based on approximate analytical formulations. A description of this option is also contained in this report.

The entire process of computing the wind and current loading on a surface ship is summarized in flow chart form in Figures 3-1 and 3-2 at the end of this report. It should be noted that Figure 3-1 represents a further definition of the first block of the DSSM Static Analysis Macro-flow Chart presented in Letter Report No. 2. Figure 3-2 represents a subroutine which will be called whenever the evaluation of ship's loads is required.

DISCUSSION

The Experimental Loading Functions

The DM-26 procedure begins with a set of load measurements obtained from subscale tests on a representative ship's model. The measurements give the values of the lateral and longitudinal forces and yawing moment versus wind and current headings relative to the bow of the ship. These measurements represent the combined effects of such phenomena as profile and friction drag, life induced side forces and shifts in the center of pressure.

Test results for nine vessels are given in DM-26. Of those nine, two are used extensively to represent other ships in the fleet. These two are the EC-2 (Liberty Ship) and the DD-692 (Destroyer). DM-26 presents curves for one wind velocity and three current velocities for these two ships.

Digital representations of the loading curves are required in the DSSM program. The curves will be represented by a set of tables relating velocity, heading and load. Three tables will be provided at each velocity (one each for lateral force, longitudinal force and yaw moments). Each of these tables will be assumed to have up to 20 points. Judging from the data in DM-26 this should allow for adequate definition of the curves using linear interpolation between the points. The DSSM program will also be dimensioned to allow curves to be input for up to five velocities in both wind and current.

As mentioned in Letter Report No. 2, a file of ship's loading data can be generated and then used to select the appropriate loading function when it is required in the static analysis. Data for generating this file for the EC-2 and DD-692 based on the DM-26 curves will be provided with the DSSM program. The user of the DSSM program will also have the option of adding to this file or specifying the values of the loading functions to be used (via card input) during a particular static analysis.

Use of the Loading Curves in the DSSM Static Analysis

When using the experimental functions after the manner of DM-26 the loading conditions are determined from the magnitude and heading of the wind and surface current velocities. It is assumed that the specified magnitudes are representative of the values of wind and current at their respective centers of pressure; therefore, no adjustments are made for the vertical distribution of the velocities.

Given the headings of the wind and current, the forces are obtained from the experimental curves using linear interpolation between the points in the appropriate loading table. In the event that there are tables provided for more than one velocity, the table for the velocity nearest the one specified in the analysis will be used. This will be determined by comparing the squares of the velocity ratios.

After the loading values have been obtained from the tables, they must be scaled to account for differences between the conditions modeled in the test and those being analyzed. The following three differences will be treated by scaling in the DSSM program:

1 Velocity of wind and current

2 water depth

3 geometry of the ship

Equations for Ship Loading (DM-26)

The formulas for adjusting for the effects noted above are given in DM-26, and they are restated here for completeness.

WIND

$$F_s = C_f V^2 F_{ms} A_s/A_{ts} \tag{3-1}$$

$$F_e = C_f V^2 F_{me} A_e/A_{te} \tag{3-2}$$

$$M_w = C_m V^2 M_m A_s L/A_{ts} L_t \tag{3-3}$$

where

F_s = lateral force on ship

F_e = longitudinal force on ship

M_w = yawing moment on ship

F_{ms} = lateral force on model

F_{me} = longitudinal force on model

M_m = yawing moment on model

V = wind velocity

A_s = side-projected areas above the water line of ship being analyzed

A_{ts} = side-projected area above the water line of modeled ship

A_e = end-projected area above the water line of ship being analyzed

A_{te} = end-projected area above the water line of modeled ship

L = Length of ship being analyzed

L_t = Length of modeled ship

$$C_f = \frac{S^2}{V_T^2} \tag{3-4}$$

$$C_m = \frac{S^3}{V_T^2} \tag{3-5}$$

S = linear scale of the model

V_T = wind velocity used in model test

CURRENT

$$h_2 = h_1 L_{W2}/L_{W1} \tag{3-6}$$

$$V_1 = V_2\sqrt{L_{W1}/L_{W2}} \tag{3-7}$$

$$F_2 = F_1 \Delta_2/\Delta_1 \tag{3-8}$$

$$M_2 = M_1 \Delta_2 L_{W2}/\Delta_1 L_{W1} \tag{3-9}$$

where

h = depth of water

V = velocity of current

L_W = water line length of vessel

F = lateral or longitudinal resisting force

M = yaw resisting moment

Δ = displacement

Subscript 1 denotes the vessel for which the test was made, and subscript 2 denotes the vessel being analyzed.

When the velocity from equation (3-7) does not correspond to one of the tables given for the model test then the forces and moments will be selected from the tables corresponding to the velocity nearest the value of V_1 in equation (3-7). It will then be necessary to adjust the values by the square of the ratio of the V_1 velocity and the velocity represented in the tables, V_{t1}.

It is quite likely that the depth at the proposed mooring site will not be the same as that obtained for h_2 in equation (3-6). In that event, a correction for depth is required. DM-26 suggests that the correction be made assuming an inverse relationship with the side resistances at the two depths in question. The curves given in Graph 124 (EC-2) of DM-26 will be used along with equation (3-6) for this purpose. The data will be given in tabular form and the side resistances will be obtained by logarithmic interpoation. The resistance for a depth greater than that in the table will be the last value in the table.

The adjustments for current velocity and depth are summarized by the following equations:

$$F'_{s2} = f_h \frac{V_1^2}{V_{t1}^2} F_{s2} \tag{3-10}$$

$$F'_{e2} = f_h\left(\frac{V_1^2}{V_{t1}^2} F_{e2} - \frac{1}{2}\rho C_p A V_2^2\right) + \frac{1}{2}\rho C_p A V_2^2 \tag{3-11}$$

$$M'_2 = f_h \frac{V_1^2}{V_{t1}^2} M_2 \tag{3-12}$$

where

f_h = the depth scaling factor

V_{t1} = the velocity at which the test data was obtained

A = the propeller projected area

C_p = the propeller drag coefficient

The primes indicate the value adjusted to the desired conditions for the mooring site. Equation (3-11) reflects the adjustment in the longitudinal force recommended by DM-26 with the assumption that $\frac{1}{2}\rho C_p = 2.88$. Assuming the specific weight of sea water is 64 lb/ft^3 and the acceleration due to gravity is 32.2 ft/sec^2 then $C_p = 2.90$. The form using $1/2\rho\ C_p$ rather than 2.88 is required to make the procedure dimensionally independent.

Equivalent Ship Selection Procedure

DM-26 suggests that many of the ships in the fleet can be approximately modeled by scaling from one of a limited number of test vessels. In fact, Table 7-4 of DM-26 suggests that a major portion of the fleet can be simulated from either the EC-2 or DD-692 test data. The work statement stipulates (Work Package 1, Task 2, Item A1) that the static portion of the DSSM shall have the capability of selecting an equivalent ship from among the nine test vessels in DM-26. Although the desirability of such a feature is clearly seen, an accurate algorithm for accomplishing the selection with a small number of test vessels cannot be expected. The variety of hull shapes and super structure arrangements lead to a requirement for specifying much more detailed geometric data than is readily available or convenient to use if one attempts to define an accurate algorithm.

Admitting the very rough nature of any convenient selection algorithm, a number of simple parameters were investigated to determine if they would be able to identify a suitable equivalent ship. It was decided that no data beyond that given in Table 7.4 of DM-26 would be used in the selection process. This decision was made on the presumption that the collection of any data beyond that in Table 7.4 would be a major undertaking. Five measures of ship similarity were tested against Table 7.4 to determine if any of them singly or in combination would lead to the same choice of equivalent ship as given in the Table. The five measures are listed below with their values for the EC-2 and DD-692:

TABLE 1

SHIP SIMILARITY MEASURES

FORMULA	EC-2	DD-692
Wind Area Ratio - A_s/A_e	4.95	7.3
Displacement Distribution Factor - Δ/L_W	13.4	6.2
Length-Breadth Ratio - L/B	7.75	9.2
Block Coefficient - Δ (lbs)/LBH	39.8	30.3
Displacement-Length Ratio - Δ (Tons)/$(L/100)^3$	63.7	42.9

B = beam amidships

H = draft amidships

The wind area ratio appears to be the only measure of similarity in wind load behavior that is available from the data in DM-26. The remaining quantities are measures of hull similarity. These measures were applied to various of the ships listed in Table 7.4 in DM-26 and the results are presented in Table 2. The underlined values indicate a lack of agreement with the equivalent ship selection in DM-26.

The most consistent measure appears to be the block coefficient. It is significant to note that the wind area ratio does not seem very reliable. This could either mean that the measure is a poor one or that the choice was made primarily on the basis of hull similarity. A comparison of Graphs 18 and 31 in DM-26 shows that the general form of the wind loading curves for both the EC-2 and DD-692 are quite similar. The major difference is in the yawing moment where the DD-692 has a much smaller moment for attack angles between 90 and 270 degrees. Comparing Graphs 125 and 130 reveals that there are much more significant differences in current loading curves. Thus it would appear that in the case of selecting between the EC-2 and the DD-692 the hull similarity should be the determining factor. If the choice was to be made from among more than just these two ships it would seem that more reliable ship equivalency measures are needed. A search for such measures does not seem justified at this point. Thus, the procedure to be employed in the DSSM program will involve the calculation of the nondimensionalized form of the block coefficient (displacement volume/LBH) then the file of ship's loading data will be searched for the ship which has the block coefficient closest to that value. In the event that the computer program user does not feel that this selection procedure will give him the appropriate equivalent ship he may simply specify which ship on the data file is to be used. An overview of the process is shown in block diagram form in Figure 3-1.

Analytical Form of Ship Loading Functions

As an alternative to the experimental loading functions, the DSSM static solution will provide an optional analytical form. Because of the difficulty in obtaining detailed data on some ships, these functions will utilize only data of the type presented in Table 7.4 of DM-26 with only minor exceptions.

TABLE 2

COMPARISON OF SHIP SELECTION MEASURES

Class	A_s/A_e	Δ/L_W (Tons/ft)	L/B	Δ/LBH (lbs)	$\Delta/(L/100)^3$ (Tons/10^{-6}ft^3)	DM-26 Equiv. Ship
AD-14	5.0	19.5	7.3	37.7	67.0	EC-2
AD-26	6.7	17.4	7.0	36.2	66.4	EC-2
AF-30	4.6	10.3	6.8	43.8	84.2	EC-2
AG-127	6.2	5.8	10.3	29.97	38.9	DD-692
AO-22(T3)	5.7	13.8	7.4	36.5	42.8	EC-2
ARS-6	3.5	6.5	5.5	32.9	137.8	EC-2
AS-11	6.0	18.6	7.3	37.6	65.0	DD-692
AS-23	5.8	16.5	7.0	35.9	64.5	DD-692
ASR-7	5.8	6.6	6.0	27.98	99.9	DD-692
ATA-121	3.5	4.6	4.2	26.7	212.0	DD-692
AV-7	6.1	17.4	7.8	38.0	57.3	EC-2
BB-61	5.1	5.1	8.2	35.7	62.7	DD-692
DE-339	6.3	3.7	8.3	26.5	38.4	DD-692
LSD-1	4.7	10.1	6.4	28.4	47.9	DD-692
LSV-1	4.4	11.6	6.5	28.1	54.6	DD-692
YO-46	5.2	4.3	6.4	41.5	73.2	EC-2

The following equation (based on the work of Hughes*) will be used to approximate the wind loading:

$$F = K\rho_a V^2 (A_e \sin^2 \theta + A_s \cos^2 \theta)/\cos(\alpha - \theta) \qquad (3\text{-}13)$$

where

K = constant, 0.6

F = resultant wind force

ρ_a = density of air

V = wind velocity

*Hughes, G., "The Air Resistance of Ship's Hulls with Various Types and Distributions of Superstructures," IESS, 1932.

θ = wind heading relative to the bow

α = heading of the resultant wind force relative to the bow

The heading of the resultant force, α, is approximated as a function of θ in a 7^{th} order polynomial as follows:

$$\begin{aligned}\alpha = {} & 0.0715608 + 7.954381\theta - 0.3254561\theta^2 \\ & + 0.0073131\theta^3 - 9.3966 \times 10^{-5}\theta^4 \\ & + 6.85008 \times 10^{-7}\theta^5 - 2.6323 \times 10^{-9}\theta^6 \\ & + 4.1453 \times 10^{-12}\theta^7 \end{aligned} \qquad (3\text{-}14)$$

In equation (3-14) both θ and α are measured in degrees.

The distance between the ship forward perpendicular and the center of wind pressure, X_{cp}, can be approximated as a polynomial function of the wind direction, θ. This relationship is

$$\begin{aligned}\frac{X_{cp}}{L} = {} & 0.2004112 + 0.0048641\theta - 4.52442 \times 10^{-5}\theta^2 \\ & + 5.45736 \times 10^{-7}\theta^3 - 3.78789 \times 10^{-9}\theta^4 \\ & + 1.02881 \times 10^{-11}\theta^5 \end{aligned} \qquad (3\text{-}15)$$

Here, as above, θ is measured in degrees. The yawing moment due to wind is then approximated by

$$M_W = FL \sin\alpha \left(\frac{1}{2} - \frac{X_{cp}}{L} \right) \qquad (3\text{-}16)$$

Analytical expressions for the resistances from current effects will utilize the approach presented by Altman.* These expressions are summarized below:

$$F_s = F_{s\infty} \left(1. + \frac{10.}{(h/H)^2 - 1.}\right) \qquad (3\text{-}17)$$

$$F_{s\infty} = 0.215\, \rho_W V^2 L_W H \sin\theta \qquad (3\text{-}18)$$

*Altman, R., "Forces on Ships Moored in Protected Waters," HYDRONAUTICS, INC. Tech Rept. 7096-1, July 1971.

$$F_e = \frac{1}{2}\rho_w V^2 (S_w C_R + AC_p) \cos\theta \qquad (3\text{-}19)$$

$$S_w = C_s \sqrt{\nabla L_W} \qquad (3\text{-}20)$$

where

∇ = displaced volume

C_s = wetted surface coefficient, input with ship description

C_R = hull resistance coefficient, input with ship description or calculated as $C_r + C_f + 0.0005$ (3-21)

C_r = residuary resistance coefficient

C_f = frictional resistance coefficient, $= \dfrac{0.456}{(\log_{10} R_e)^{2.58}} - \dfrac{1700}{R_e}$ (3-22)

R_e = Reynolds number for the hull

$$M = F_s L_{CP} \qquad (3\text{-}23)$$

L_{CP} = distance from midships to hull center of pressure

$$L_{CP} = L\,[\bar{L}_{90} - 0.00226\,(\theta - 90^0)] \text{ for } 0^0 \leq \theta \leq 180^0$$

$$L_{CP} = L\,[\,\bar{L}_{90} + 0.00226\,(\theta - 270^0)] \text{ for } 180^0 \leq \theta \leq 360^0 \qquad (3\text{-}24)$$

$\bar{L}_{90}$ = ratio of distance to center of pressure at $\theta = 90^0$ to the distance to the center of hull side area

Various of these terms require further discussion. The ~~wetted surface~~ hull resistance coefficient , C_R, represents the sum of various coefficients for different sources of hull resistance. This coefficient may be input or calculated in the computer program. When no input is given for C_R it will be calculated as the sum of a residuary resistance coefficient, a frictional resistance coefficient, and a fouling/surface effect coefficeint. The fouling/surface effect coefficient will be given an arbitrary value of 0.0005. The frictional coefficient will be calculated from equation (3-22) and the residuary coefficient will be obtained from linear interpolation in a digitized form of Figure 38 of the Altman report. This method of obtaining C_r is limited to low flow velocities since wave-making resistances are ignored.

The longitudinal location of the center of pressure for a hull skewed with respect to the flow is estimated by equations (3-24). This requires an estimate of the ratio of the distance to the center of pressure and the center of area for beam flow, $\bar{L}_{90}$. This factor will be estimated by linear interpolation between the values for the DD-692 and EC-2 using the block coefficient as a reference. That this approach is reasonable is suggested by the previous discussion of selection of an equivalent ship and the data presented by Altman in his Figure 50. Altman gives the values for $\bar{L}_{90}$ for the DD-692 and EC-2 as 0.056 and -0.138, respectively. (Negative means aft of midships.)

It should be emphasized that these analytical expressions are to be viewed as a convenient alternative to the DM-26 experimental curve procedure. They are not represented as highly accurate, and it remains to be demonstrated that they are capable of giving reliable approximations of the ships loading. The forces predicted by these expressions will be compared to the DD-692 and EC-2 experimental curves as a matter of course during the checkout of the program. It should be noted, however, that any further improvements or refinements in these expressions is not contemplated during this contract.

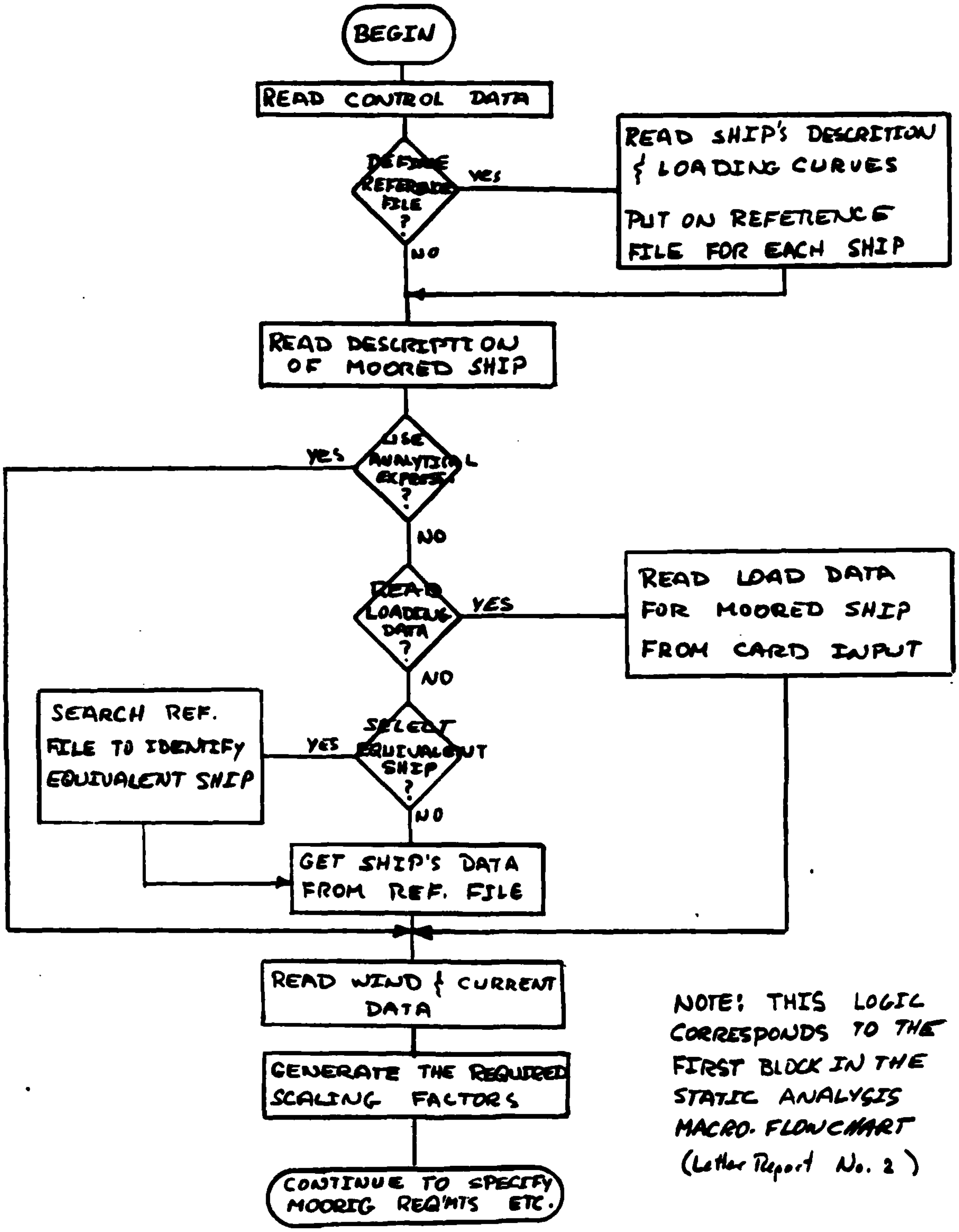

FIGURE 3-1. LOGIC FOR DEFINING SHIP'S DATA IN DSSM STATIC ANALYSIS

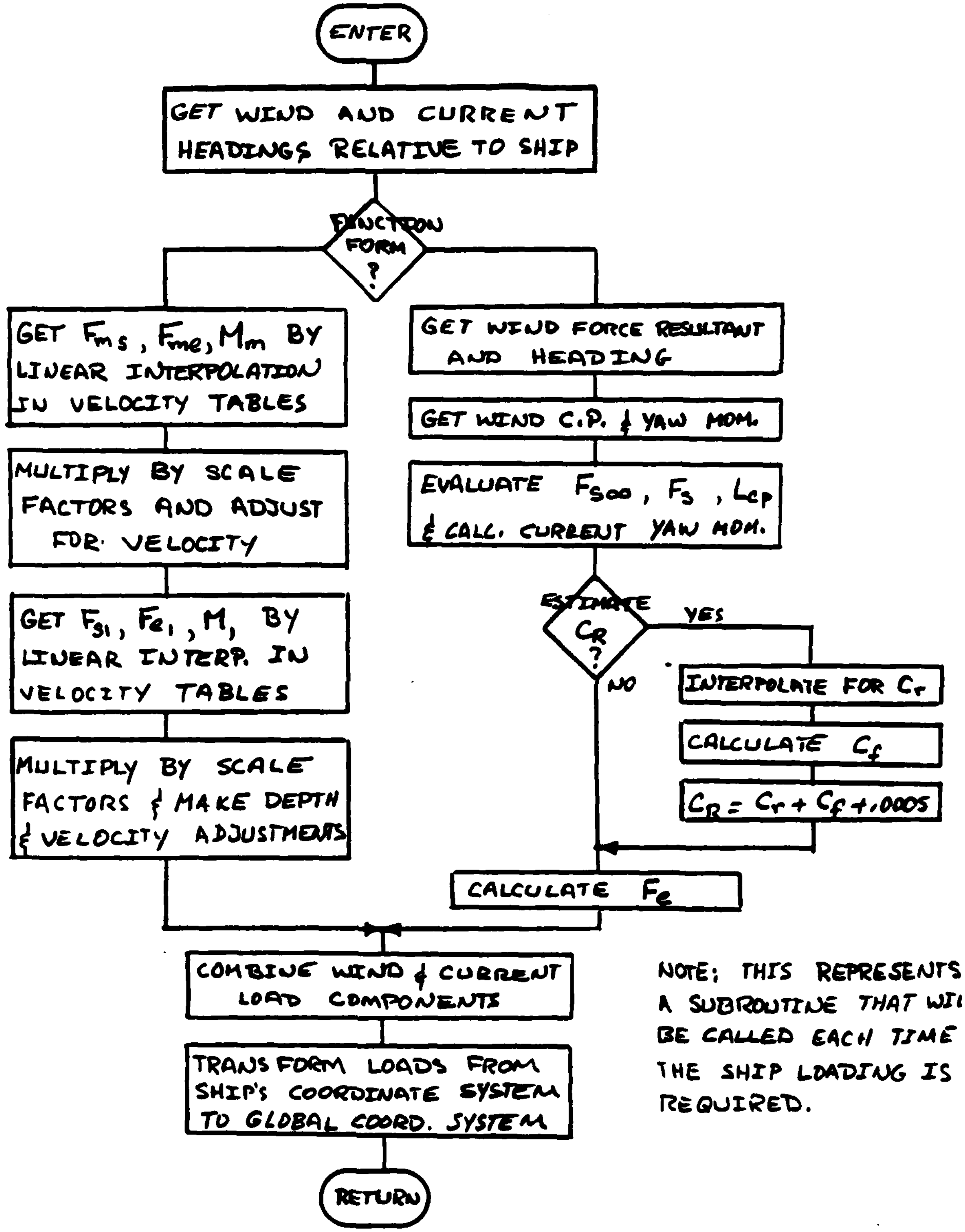

FIGURE 3-2. PROCEDURE FOR EVALUATING SHIP'S LOADING

LETTER REPORT NO. 4

DEVELOPMENT OF STATIC MOOR CONFIGURATION ANALYSIS
(WORK PACKAGE 1, TASK 3)

CONTRACT NUMBER N62477-76-C-0002

BY: R. L. Webster

23 FEBRUARY 1976

Electronics Systems Division
The General Electric Company
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This Letter Report is submitted in compliance with item no. (4) of the Milestones and Deliverables Schedule of Contract N62477-76-C-002 dated 17 June 1975 as revised 4 August 1975.

TABLE OF CONTENTS

INTRODUCTION

This Letter Report describes the static portion of the DSSM computer program. The program has been written and initial phases of checkout have been completed. A full description of the procedures used and a sample output from the program are included in this report. A source file of the program will be established on the NSRDC Computer System as soon as a data transmission link is functional (approx. 3 weeks), and a copy of the source deck will be sent if requested.

The first two Letter Reports on this contract gave some preliminary descriptions of an approach to the DSSM static analysis. However, as programming effort progressed it became obvious that not all of the objectives of the static program could be met conveniently by the approach described there. A discussion of the problems encountered and their resolution are included in this report also. The crux of the difficulties centered in the differences between design and analysis; or more precisely, the differences between explicit and implicit design procedures. The first section of the discussion will attempt to show the major differences between these terms as they relate to the DSSM problem.

DISCUSSION

Explicit versus Implicit Design Procedures

The overall purpose of the DSSM computer program is to provide a tool to aid the mooring system designer in selecting a mooring configuration and a set of mooring components which meet certain performance requirements. The mooring system designer's problem can be stated:

Given a ship, a mooring site, a set of environmental conditions and a list of standard mooring components; select the arrangement of mooring lines, mooring leg material/construction, mooring leg diameters and lengths, anchors and anchor locations, and other components (buoys, hawsers, etc.) which will hold the ship within specified position and motion limits without causing damage to the ship, its pay load, or the mooring components.

There may also be various side constraints such as limitations on costs, system weight and volume,etc. Thus, the problem is one of finding an "adequate" design.

In the design process there are two basic approaches. They can be categorized as explicit and implicit procedures. An explicit design procedure formulates the problem in terms of a set of design parameters and then proceeds to solve directly for the values of those parameters which meet the design constraints. It is usually quite difficult to express general mathematical models in the explicit form, and one usually is limited to some highly idealized special cases. On the other hand, the implicit design procedures postulate values of the design parameters and then use an analysis procedure to see if the constraints are met by those parameters. Generally, the analytical methods allow for more complexity and detail than can be expressed in an explicit design model. The implicit procedures then take the form of an iteration where trial designs are postulated either from intuition or some rational procedure and then evaluated by analysis. The iteration proceeds until an adequate design is found or the resources are exhausted.

The mooring of a ship in deep waters is a very complicated problem. The governing mathematical equations are highly nonlinear and for general conditions typical of a deep water site there are no simple expressions which describe the response of the mooring system. In addition, the procedures outlined in the work statement for dealing with dynamic effects already imply an implicit approach is to be used in that case. Since a deformed static configuration of the ship and moor are required to begin the dynamic evaluations and to update for variations in the steady-state drift force, an analytical model for the static (steady-state) response of the ship and moor is required. For these reasons an implicit approach was seen to be appropriate for the DSSM static design problem. The SEADYN program was seen to possess the essential characteristics for the static analysis, and much of the effort in this work package was spent in modifying SEADYN to accommodate ships in the cable system.

Of course, the numerical/analytical model is only one of the components in an implicit design procedure. Two other components are needed before a useful design tool is obtained. First is the ability to postulate designs to be analyzed in such a way that one has a reasonable chance of finding an adequate design. Second is the ability to measure whether or not the design constraints are met after the analysis has been performed. Both of these features were absent from the SEADYN program. The most elementary form (and the most common) of implicit design procedures leaves both of these functions in the hands of the designer and the numerical/analytical model is used only to calculate responses. It being obvious that this was not the intent of the DSSM contract effort in so far as the static design was concerned, work proceeded on both of these additional features.

It was in these two areas that significant problems were encountered. From the outset it was recognized that it was not feasible to completely remove the designer from the task of postulating trial designs. The intent was to reduce the computational and judgmental burden. Initial attempts at developing procedures for postulating trial designs led either to sequential search procedures (i.e., numerical method for finding a set of parameters which minimize the deviations from the "optimum" response) or back to the explicit approach. The sequential search methods appeared to be quite costly to use and would require an unrealistic amount of time to implement. To further complicate matters, it was found that the introduction of the ship equations into the SEADYN format led to some solution instabilities which make calculations

of the responses to a large number of flow directions somewhat uneconomical. Finally, the finite element modeling procedure used in SEADYN results in some loss of detail related to the tensions and slopes at the ends of the mooring lines, thereby complicating the determination of the adequacy of the postulated design.

Some improvements in the solution stability of the SEADYN program were achieved, and an approach to evaluating the end slopes and tensions was outlined. Even with these improvements it was apparent that the exclusive use of the implicit approach would not provide the desired efficiency. Thus it was decided to return to the explicit design approach to perform the basic identification of the mooring details and then leave the SEADYN static analysis as an adjunct to allow more detailed checks of the design and to provide the starting point for the dynamic analysis.

Description of the Explicit Design Procedure

The explicit design procedures that were used in this effort deal with slack moors using the catenary equations and with taut moors assuming the lines are weightless. In the development of the equations it was necessary to make various simplifying assumptions. The major assumption in the slack moor case is that the mooring legs are catenarys which are tangent to the bottom under the extreme loading. This means that the leg lengths and anchor locations are chosen such that a portion of the mooring line lays along the bottom in the quiescent state and that the critical leg is deflected to have the anchor located at the bottom tangent point under the extreme loading. It is further assumed that all legs have the same properties and that the only loading besides the weight of the legs is that induced by wind and surface currents on the ship. The cable ultimate strengths and weight per unit length are assumed to be proportional to the square of the cable diameter. The parameters determined are the leg diameters and lengths, the locations of the anchors along pre-selected headings, and the initial horizontal load components.

The taut moor procedure assumes the legs are weightless and that the angles between the mooring legs and the vertical direction (vertex angle) is known for the quiescent state. The parameters determined are the leg diameters and the upper limit of the preloads that can be imposed in the quiescent state without exceeding the design tensions in the extreme state. Again it is assumed all legs have the same material properties and the same diameter.

Both the slack and taut procedures are based on the premise that under the extreme conditions the wind and surface currents are coincident and that the ship moves from the quiescent position a distance equal to the radius of the design watch circle. At that point the heading of the ship is iteratively adjusted until the yaw moments applied by the environmental and work loads are balanced by the mooring restoring forces. After the moment balance is achieved, the resultant of the restoring forces is checked to see if it is collinear with the resultant of the external loads. If not, the position of the ship's c.g., on the watch circle is adjusted until both the moments and lateral forces are in balance.

The loads which are resisted by the mooring lines are assumed to be the vector sum of the environmental loads applied to the ship by surface currents and wind and the work loads. The components of the ship environmental loads are calculated at each stage of the iterations. The procedures described in Letter Report # 3 are used in this calculation. The calculation takes account of the change of orientation of the ship with respect to the flow. The work loads are assumed to remain fixed in their global orientation as the ship is displaced; therefore, the components of the forces do not change but the moment due to them does.

The diameter of the mooring legs is selected to provide the required magnitude of lateral resistance without exceeding the limit tension. Various flow headings are tried and the largest diameter found is used in the mooring design.

The equations used in this explicit design procedure are summarized in the next two sections. A flow chart of the procedure is given in Figure 4.1.

The Slack Moor Equations

Figure 4.2 shows the pertinent parameters in a catenary mooring leg. The equations for the horizontal load response of a catenary leg of length S_{max} and weight per unit length, w, can be developed from the standard catenary formulae. A mooring leg under zero horizontal load hangs straight down at a distance X_{min} from the anchor. Thus

$$X_{min} = S_{max} - y_{max} \qquad (4.1)$$

The maximum conditions are limited to the case where $\overline{X} = 0$ and the catenary is tangent to the bottom at the anchor. Between these limits

$$X_c = C \ln \left(\frac{S_c + \sqrt{S_c^2 + C^2}}{C} \right) \tag{4.2}$$

where $C = H/w$ (4.3)

and H is the horizontal component of the force in the catenary. With some algebraic manipulation, Equation (4.2) can be written

$$X_c = C \ln \left(\frac{S_c + y_{max}}{S_c - y_{max}} \right) \tag{4.4}$$

and the catenary length can be written

$$S_c = \sqrt{y_{max} (y_{max} + 2C)} \tag{4.5}$$

Thus, from Figure 4.2

$$X = \overline{X} + X_c = S_{max} - S_c + X_c \tag{4.6}$$

Assuming that the ultimate strength, T_u, and the weight per unit length are proportional to the leg diameter squared gives

$$T_u = \tau d^2 \tag{4.7}$$

$$w = Kd^2 \tag{4.8}$$

Here τ and K are the proportionality constants and are material properties which can be determined for specific types of cables. For a given safety factor, S. F., the limit or working load is given by

$$T_w = T_u/S.\ F. \tag{4.9}$$

Working with the equations of equilibrium for a catenary it can be shown that

$$C_{max} = T_w/W - y_{max} \tag{4.10}$$

Then it follows from (4.10) and (4.5) that

$$S_{max} = \sqrt{2\, y_{max} \left(T_w/W - \frac{1}{2}\, y_{max}\right)} \tag{4.11}$$

Working with (4.3) and (4.8) leads to

$$\frac{H}{d^2} = kC \tag{4.12}$$

The set of equations (4.1) through (4.12) can be used to select a leg length and define a relationship between the horizontal distance, X, and the ratio H/d^2. An explicit equation for X in terms of H/d^2 can be developed from this set of equations. However, in the mooring design problem, it is the inverse of this relation that is desired. Unfortunately, the inverse relation is not obtainable from these equations. This difficulty can be circumvented by various means. The easiest to implement on the computer is a table look-up procedure. A table of kc versus X is generated for values of $0 \leq C \leq C_{max}$ and then the table is entered with a value of X and linear interpolation is used to find the corresponding H/d^2. Since S_{max} and C_{max} are determined by the water depth and material properties the table needs to be generated only once in the design. Other possibilities for getting H/d^2 for a given X include curve fitting the relation or using the method of successive approximations. The table look-up method was used in this work.

The design procedure starts with the calculation of the maximum catenary parameters and the table generation. The maximum range from the ship attachment point to the anchor is then given by X_{MAX} + HAWS, where HAWS represents the hawser length (if any). Then from a trial position of the ship on the watch circle the anchor positions are estimated using the maximum range from the attachment points on the ship and the specified lines along which the anchors must lie. These lines are specified by a heading relative to the quiescent position of the ship, and in that position all mooring legs are assumed to have the same X_c. Once the anchors are located, the distances to the respective ship attachments are used to obtain the values of H/d^2 from the table. The components of the H/d^2 values are summed vectorially to get the resultant scaled restoring force vector. The diameter of the legs is then

$$d = \sqrt{F/\bar{R}} \tag{4.13}$$

where

F is the magnitude of the ship loading vector

$\overline{R}$ is the magnitude of the scaled restoring force vector

The components of H/d^2 are then multiplied by d^2 and the difference between the ship's yaw moment and the resisting moment is calculated. The iterations described previously are used to find a position on the watch circle and a ship's heading which simultaneously balance the ships loads and yaw moment. A modified Newton procedure with the slope approximated by a backward difference is used to estimate the headings, and the position adjustments are determined with a successive approximations search for the minimum deviation from -1.0 of the normalized dot product of the external and resisting force vectors.

The Taut Moor Equations

The basic assumption used in the taut mooring design is that the legs are weightless and that they resist the external loads by the elastic deformation of the legs. By assuming that the excursions are small compared to the overall dimensions of the mooring system, the restoring forces can be expressed in terms of the linear strain in the legs. This neglects any geometric stiffening effect due to pre-loads in the legs. This is in contrast to the slack case where the elasticity effects are neglected and changes in the mooring leg forces are due entirely to geometric effects.

Since the legs are assumed weightless the tension does not vary over the length of the leg. For loadings in the linear elastic range of the leg material the following load/strain relationship can be obtained:

$$T = EA\varepsilon \qquad (4.14)$$

where

E is the effective modulus of elasticity of the mooring leg

A is the cross-sectional area

ε is the average strain

Assuming the cross-section is circular, (4.14) can be rewritten

$$T/d^2 = \frac{\pi}{4} E\varepsilon = \overline{E}\varepsilon \qquad (4.15)$$

In general the legs will have some preload in the quiescent state and the resisting forces are developed by the strain increments occurring in the motion from the quiescent to the deflected state. For small strains and linear materials the incremental modulus of elasticity is the same as the total modulus and the strain increment is given by

$$\Delta\varepsilon = \frac{L - L_o}{L_o} \tag{4.16}$$

where

L is the deformed leg length

L_o is the initial leg length

The tension increments are then given by

$$\frac{\Delta T}{d^2} = \overline{E}\,\Delta\varepsilon \tag{4.17}$$

Since the preload stiffening is being ignored the restoring forces are due entirely to the tension increments. The expression for the H/d^2 components in the deformed state can then be written

$$\frac{H}{d^2} = \frac{\Delta T}{d^2}\,\sin\left[\,\text{Arc tan}\left(\frac{B}{y_{max}}\right)\right] \tag{4.18}$$

where B is the range distance from the anchor to the ship attachment point. Therefore, using Equations (4.16) through (4.18) the H/d^2 components can be found for each leg and the solution follows the same iterative procedure described earlier to balance the moments and forces.

Once the maximum leg diameter is determined, it is possible to estimate the maximum preload that can be applied in the quiescent state and still not exceed the limit tension. In this case

$$T_{o(max)} = T_w - \Delta T_{max} = T_w - \overline{E}d^2\,\Delta\varepsilon_{max} \tag{4.19}$$

If there is sufficient preload in the quiescent state, both the elongations and contractions of the legs are effective in developing restoring forces. Obviously, the contracting legs will go slack when the load increment exceeds the preload. Since the appropriate amount of preload is not known a priori, the program allows the option of including the effects of the contracting legs in the restoring forces or deleting them. If the contracting legs are included, the maximum allowable preload and the largest compressive load increment will be output to check the validity of the assumption.

Use of the SEADYN Program in Static Moor Analysis

Although difficulties were encountered in the implementation of implicit design procedures with the SEADYN static analysis, the program provides some very useful capability for the mooring designer. First, it allows the evaluation of much more complex systems than can be treated in the explicit procedure just described. Thus one could either postulate a design and describe the quiescent configuration to SEADYN or the data from the design program can be used as the starting point. Arbitrary combinations of wind and current could then be evaluated in combination with general subsurface currents. If the work loads are due to other cable systems (e.g., array deployment), the suspended system could also be included.

SEADYN will be most useful in the particular cases that do not fit the assumptions of the explicit design program. In addition to the situations described above, this includes negative or positively buoyant legs which are not tangent at the bottom, unequal or nonuniform legs, multiple materials, nonlinear materials, interconnecting legs, etc.

The SEADYN static analysis is the logical starting point for the dynamic analyses of work package 3. In order to develop the regular wave response data for the moored ship it is necessary to have the ship in a displaced configuration and then generate a stiffness and mass matrix for the mooring system. As the regular wave calculations proceed, it is also required that the static configuration be adjusted to balance the changes in the steady-state drift force. SEADYN is well suited to both of these tasks.

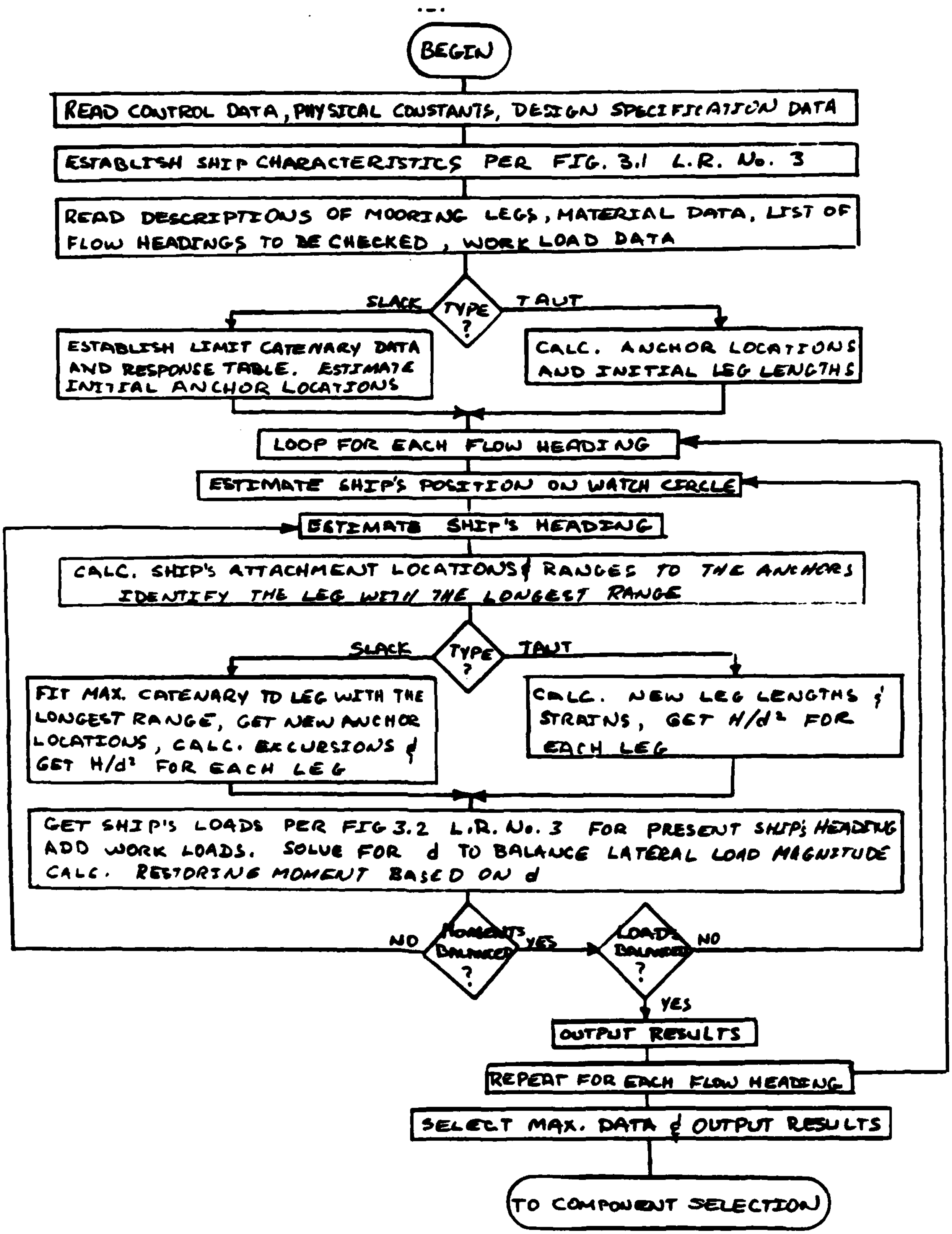


Figure 4-1. Logic Diagram for the Explicit DSSM Static Design Procedure

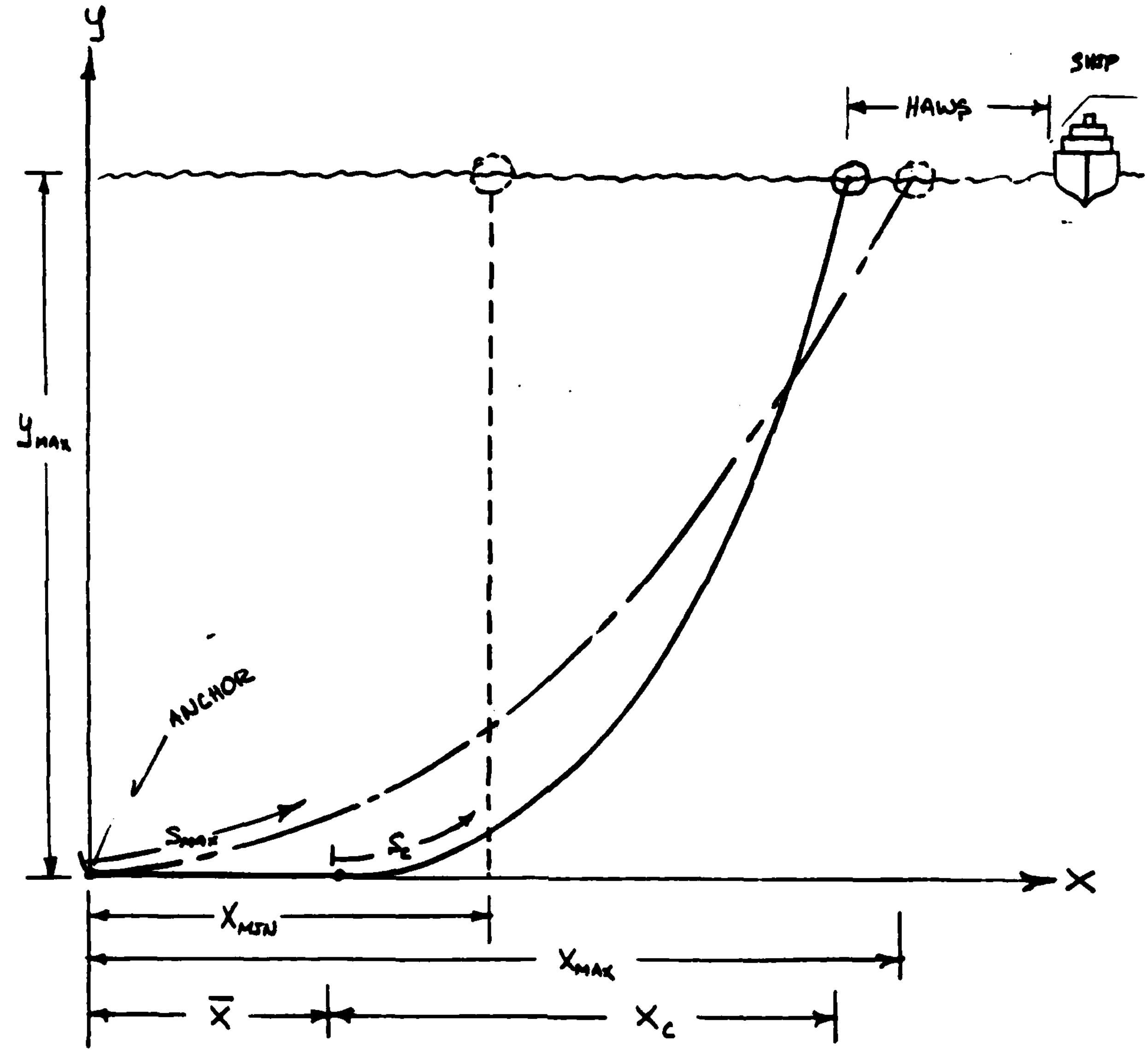


Figure 4-2. Catenary Parameters

EXAMPLE DESIGN PROBLEM

PROBLEM DESCRIPTION

Four point moor of U. S. S. Aeolus, ARC No. 3 in 15,000 ft. of water with slack legs.

Watch Circle Radius	500 ft.
Design Wind Velocity	16 Knots
Design Current Velocity	0.5 Knots
Work Loads	7.5 K at 42° off bow
Factor of Safety	3.0
Wind Load Factor	1.33

Cable Material Data

$\tau = 9.936 \times 10^4$ lb/in.^{2}

$k = 1.44$ lb/ft-in.^{2}

$T_u = 158{,}000$ lbs.

DESIGN RESULTS

Maximum Cable Diameter	1.85 in.
Catenary Weight/Length	4.9 lb/ft.
Critical Flow Heading	110 Degrees

DEEP SEA SHIP MOOR DESIGN PROGRAM

SLACK MOORING OF AEOLUS FOR 500 FT. RADIUS

MOORING TYPE = SLACK

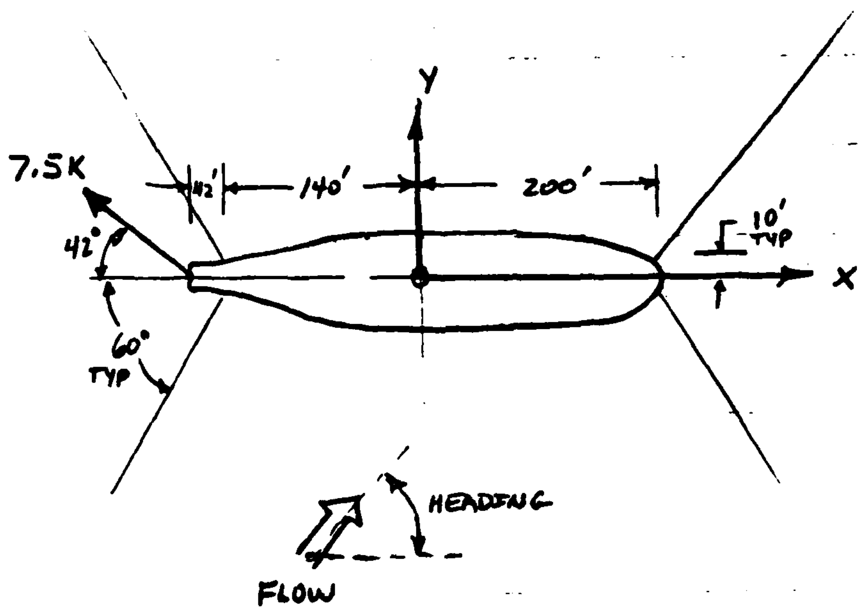
NO. OF MOORING LEGS = 4
NO. OF SHIPS ON FILE = 1
SHIPS LOADING OPTION = 1
NO. OF HEADINGS USED = 9
NO. OF WORKING LOADS = 1

GRAVITATIONAL ACCELERATION = 0.32200E 02
KINEMATIC VISCOSITY OF WATER = 0.17700E-04
SPECIFIC WEIGHT OF WATER = 0.64000E 02
SPECIFIC WEIGHT OF AIR = 0.76500E-01

DESIGN PARAMETERS

FACTOR OF SAFETY = 3.00
LOAD FACTOR = 1.33

EXCURSION RADIUS = 0.50000E 03
ULT. LEG TENSION = 0.15800E 06
WIND VELOCITY = 0.27000E 02
SURFACE CURRENT = 0.84390E 00
WATER DEPTH = 0.18000E 05



SHIPS REFERENCE FILE DATA

SHIP 1

NO. OF WIND TABLES 1 WITH 13 HEADINGS
NO. OF CURRENT TABLES 1 WITH 7 HEADINGS

SCALE FACTOR 73.80 TEST DEPTH 0.25000E 02

TOTAL LENGTH	END WIND AREA	SIDE WIND AREA	W.L. LENGTH
0.37700E 03	0.14000E 04	0.10180E 05	0.36980E 03
BEAM	**DRAFT**	**DISPLACEMENT**	**PROPS. AREA**
0.41000E 02	0.10620E 02	0.48832E 07	0.14180E 03

BLOCK COEFFICIENT 0.47489E 00

WIND VELOCITY = 0.21098E 03

HEADING (DEG)	LOAD COEFFICIENTS END	SIDE	MOMENT
0.	0.10000E 02	0.	0.
30.00	0.90000E 01	0.47000E 02	-0.[illegible]6000E 02
60.00	0.60000E 01	0.76000E 02	-0.[illegible]3000E 02
90.00	0.50000E 01	0.86000E 02	-0.[illegible]4000E 02
120.00	-0.15000E 01	0.80000E 02	0.[illegible]000E 0[illegible]
150.00	-0.11000E 02	0.47000E 02	0.[illegible]000E 0[illegible]
180.00	-0.10000E 02	0.	-0.[illegible]000E 0[illegible]
210.00	-0.11000E 02	-0.50000E 02	-0.[illegible]000E 0[illegible]
240.00	-0.15000E 01	-0.80000E 02	-0.[illegible]000E 0[illegible]
270.00	0.50000E 01	-0.88000E 02	0.25000E 02
300.00	0.60000E 01	-0.77000E 02	0.[illegible]2000E 02
330.00	0.90000E 01	-0.41000E 02	0.[illegible]5000E 02
360.00	0.10000E 02	0.	0.

CURRNT VELOCITY = 0.67512E 01

HEADING (DEG)	LOAD COEFFICIENTS END	SIDE	MOMENT
0.	0.11200E 05	0.	0.
30.00	0.11200E 05	0.94080E 05	-0.[illegible]7272E 07
60.00	0.10080E 05	0.21280E 06	-0.[illegible]7272E 07
90.00	0.56000E 04	0.26432E 06	-0.31360E 0[illegible]
120.00	-0.56000E 04	0.21280E 06	0.[illegible]344[illegible]E 0[illegible]
150.00	-0.13400E 05	0.94080E 05	0.[illegible]720[illegible]E 05
180.00	-0.13400E 05	0.	0.

DATA FOR MOORED SHIP

COEFFICIENTS

PROP. RESISTANCE	HULL RESISTANCE	WETTED SURFACE
0.	0.	0.

TOTAL LENGTH	END WIND AREA	SIDE WIND AREA	W.L. LENGTH
0.42600E 03	0.23000E 04	0.13895E 05	0.40080E 03

BEAM	DRAFT	DISPLACEMENT	PROP. AREA
0.58200E 02	0.15500E 02	0.15859E 08	0.

BLOCK COEFFICIENT 0.68673E 00

M O O R I N G   L E G   D A T A

X	Y	HEADING	VERTEX ANGLE	HAWSER LENGTH
-0.14000E 03	0.10000E 02	0.12000E 03	0.	0.
-0.14000E 03	-0.10000E 02	0.24000E 03	0.	0.
0.20000E 03	-0.10000E 02	0.30000E 03	0.	0.
0.20000E 03	0.10000E 02	0.60000E 02	0.	0.

M A T E R I A L   D A T A

STRENGTH AND WEIGHT COEFS. = 0.99360E 05 0.14400E 03

D E S I G N   H E A D I N G S

50.00	60.00	70.00	80.00	90.00
100.00	110.00	120.00	130.00	

W O R K   L O A D S

FX	FY	MOMENT	DELX	DELY
-0.55740E 04	0.50180E 04	0.	-0.10250E 05	0.

MAXIMUM CATENARY PARAMETERS

T/W	C	SMAX	XMAX	XMIN
0.23000E 05	0.80000E 04	0.21364E 05	0.13740E 05	0.65639E 04

VALUES OF X AND H/D**2

0.72438E 04	0,23040E 03
0.77069E 04	0,46080E 03
0.80912E 04	0,69120E 03
0.84258E 04	0,92160E 03
0.87247E 04	0,11520E 04
0.89958E 04	0,13824E 04
0.92445E 04	0,16128E 04
0.94748E 04	0,18432E 04
0.96889E 04	0,20736E 04
0.98895E 04	0,23040E 04
0.10078E 05	0,25344E 04
0.10256E 05	0,27648E 04
0.10425E 05	0,29952E 04
0.10589E 05	0,32256E 04
0.10739E 05	0,34560E 04
0.10882E 05	0,36864E 04
0.11021E 05	0,39168E 04
0.11153E 05	0,41472E 04
0.11281E 05	0,43776E 04
0.11403E 05	0,46080E 04
0.11520E 05	0,48384E 04
0.11635E 05	0,50688E 04
0.11743E 05	0,52992E 04
0.11848E 05	0,55296E 04
0.11950E 05	0,57600E 04
0.12048E 05	0,59904E 04
0.12143E 05	0,62208E 04
0.12235E 05	0,64512E 04
0.12325E 05	0,66816E 04
0.12411E 05	0,69120E 04
0.12495E 05	0,71424E 04
0.12577E 05	0,73728E 04
0.12657E 05	0,76032E 04
0.12734E 05	0,78336E 04
0.12809E 05	0,80640E 04
0.12882E 05	0,82944E 04
0.12953E 05	0,85248E 04
0.13023E 05	0,87552E 04
0.13091E 05	0,89856E 04
0.13157E 05	0,92160E 04
0.13221E 05	0,94464E 04
0.13283E 05	0,96768E 04
0.13346E 05	0,99072E 04
0.13400E 05	0,10138E 05
0.13465E 05	0,10368E 05
0.13522E 05	0,10598E 05
0.13578E 05	0,10829E 05
0.13633E 05	0,11059E 05
0.13740E 05	0,11520E 05

SOLUTION FOR FLOW HEADING 50.0000 CONVERGED IN 18 CYCLES
LEG DIAMETER = 0.17308E 01
MAX HOR FORCE = 0.34509E 05
MAX VERT FORCE = 0.39786E 05

HEADING TO C.G. = 104.5000
SHIPS HEADING = 348.7789

C.G. COORDINATES = -0.12519E 03 0.48407E 03

SHIPS LOAD COMPONENTS = -0.19880E 04 0.17105E 05 [illegible]E 07

REFERENCE DATA FOR SLACK MOOR

HORIZONTAL DISTANCE FROM SURFACE POINT TO ANCHOR = [illegible] 05

LENGTH OF CABLE ON BOTTOM = 0.90195E 03
INITIAL HORIZONTAL FORCE = 0.29033E 03
WEIGHT PER UNIT LENGTH = 0.43136E 01

ANCHOR LOCATIONS

LEG	X	Y
1	-0.67841E 04	0.11518E 05
2	-0.67841E 04	-0.11518E 05
3	0.68441E 04	-0.11518E 05
4	0.68441E 04	0.11518E 05

```
SOLUTION FOR FLOW HEADING   60.0000          CONVERGED IN   1   CYCLES
         LEG DIAMETER    =   0.17595E 01
         MAX HOR  FORCE  =   0.33663E 05
         MAX VERT FORCE  =   0.38754E 05

HEADING TO C.G.  =  104.5000
SHIPS HEADING    =  349.8597

C.G. COORDINATES =   -0.12519E 03    0.48407E 03

SHIPS LOAD COMPONENTS =  -0.28877E 04    0.17644E 05   [illegible]E 07

REFERENCE DATA FOR SLACK MOOR

HORIZONTAL DISTANCE FROM SURFACE POINT TO ANCHOR =    0.13285E 05

LENGTH OF CABLE ON BOTTOM =    0.90704E 03
INITIAL HORIZONTAL FORCE  =    0.29973E 05
WEIGHT PER UNIT LENGTH    =    0.44579E 01

ANCHOR LOCATIONS
LEG        X              Y
 1   -0.67827E 04    0.11516E 05
 2   -0.67828E 04   -0.11516E 05
 3    0.68427E 04   -0.11516E 05
 4    0.68427E 04    0.11516E 05
```

```
SOLUTION FOR FLOW HEADING   70.0000           CONVERGED IN    1   CYCLES
          LEG DIAMETER   =   0.17876E 01
          MAX HOR  FORCE =   0.36814E 05
          MAX VERT FORCE =   0.37663E 05

HEADING TO C.G. =  104.5000
SHIPS HEADING   =  350.8735

C.G. COORDINATES =   -0.12519E 03    0.48407E 03

SHIPS LOAD COMPONENTS =   -0.25917E 04    0.18220E 05    [illegible]E 07

REFERENCE DATA FOR SLACK MOOR

HORIZONTAL DISTANCE FROM SURFACE POINT TO ANCHOR =    0.[illegible] 05

LENGTH OF CABLE ON BOTTOM =     0.91458E 03
INITIAL HORIZONTAL FORCE  =     0.30892E 0[illegible]
WEIGHT PER UNIT LENGTH    =     0.46017E 01

ANCHOR LOCATIONS
LEG          X              Y
 1    -0.67814E 04    0.11513E 05
 2    -0.67814E 04   -0.11513E 05
 3     0.68414E 04   -0.11513E 05
 4     0.68414E 04    0.11513E 05
```

```
SOLUTION FOR FLOW HEADING    80.0000          CONVERGED IN    1   CICLES
         LEG DIAMETER   =    0.18145E 01
         MAX HOR  FORCE =    0.37930E 05
         MAX VERT FORCE =    0.36539E 05

HEADING TO C.G. =  104.5000
SHIPS HEADING   =  351.8074

C.G. COORDINATES =   -0.12519E 03    0.48307E 03

SHIPS LOAD COMPONENTS =   -0.25949E 04    0.18773E 05    [illegible]E 07

REFERENCE DATA FOR SLACK MOOR

HORIZONTAL DISTANCE FROM SURFACE POINT TO ANCHOR =    0.[illegible] 05

LENGTH OF CABLE ON BOTTOM =     0.91902E 0[illegible]
INITIAL HORIZONTAL FORCE  =     0.31799E 05
WEIGHT PER UNIT LENGTH    =     0.47612E 01

ANCHOR LOCATIONS
LEG         X              Y
 1    -0.67802E 04    0.11511E 05
 2    -0.67802E 04   -0.11511E 05
 3     0.68402E 04   -0.11511E 05
 4     0.68402E 04    0.11511E 05
```

```
SOLUTION FOR FLOW HEADING    90.0000         CONVERGED IN    4   CYCLES
          LEG DIAMETER    =   0.18280E 01
          MAX HOR  FORCE  =   0.38493E 05
          MAX VERT FORCE  =   0.35945E 05

HEADING TO C.G. =  107.5000
SHIPS HEADING   =  352.4037

C.G. COORDINATES =   -0.15035E 03    0.47686E 03

SHIPS LOAD COMPONENTS =  -0.30894E 04    0.18695E 05   [illegible]

REFERENCE DATA FOR SLACK MOOR

HORIZONTAL DISTANCE FROM SURFACE POINT TO ANCHOR =    0.13223E 05

LENGTH OF CABLE ON BOTTOM =    0.93295E 03
INITIAL HORIZONTAL FORCE  =    0.32179E 05
WEIGHT PER UNIT LENGTH    =    0.48117E 01

ANCHOR LOCATIONS
LEG          X              Y
 1    -0.69763E 04    0.11504E 05
 2    -0.69763E 04   -0.11504E 05
 3     0.68363E 04   -0.11504E 05
 4     0.68363E 04    0.11504E 05
```

```
SOLUTION FOR FLOW HEADING  100?0000          CONVERGED IN    4   CYCLES
          LEG DIAMETER   =    0?18347E 01
          MAX HOR  FORCE =    0?38778E 05
          MAX VERT FORCE =    0?35638E 05

HEADING TO C.G. =  110.5000
SHIPS HEADING   =  352.9019

C.G. COORDINATES =    -0.17510E 03    0.46834E 03

SHIPS LOAD COMPONENTS =   -0.36470E 04    0.184526 05    -0?58438E 07

REFERENCE DATA FOR SLACK MOOR

HORIZONTAL DISTANCE FROM SURFACE POINT TO ANCHOR =    0?13256E 05

LENGTH OF CABLE ON BOTTOM =      0.94410E 03
INITIAL HORIZONTAL FORCE  =      0.32343E 05
WEIGHT PER UNIT LENGTH    =      0.48473E 01

ANCHOR LOCATIONS
LEG        X              Y
 1    -0.67732E 04    0.11499E 05
 2    -0.69732E 04   -0.11499E 05
 3     0.68332E 04   -0.11499E 05
 4     0.68332E 04    0.11499E 05
```

```
SOLUTION FOR FLOW HEADING  110?0000         CONVERGED IN     4   CYCLES
         LEG DIAMETER    =   0?18435E 01
         MAX HOR  FORCE  =   0?39150E 05
         MAX VERT FORCE  =   0?35228E 05

HEADING TO C.G. =  113.5000
SHIPS HEADING   =  353.4120

C.G. COORDINATES =   -0.10937E 03    0.45853E 03

SHIPS LOAD COMPONENTS =   -0.42024E 04    0.18201E 05   -0?93871E 06

REFERENCE DATA FOR SLACK MOOR

HORIZONTAL DISTANCE FROM SURFACE POINT TO ANCHOR =    0.13282E 05

LENGTH OF CABLE ON BOTTOM =     0.95297E 03
INITIAL HORIZONTAL FORCE  =     0.32594E 05
WEIGHT PER UNIT LENGTH    =     0.48938E 01

ANCHOR LOCATIONS
LEG        X              Y
 1   -0.67708E 04    0.11495E 05
 2   -0.67708E 04   -0.11495E 05
 3    0.68308E 04   -0.11495E 05
 4    0.68308E 04    0.11495E 05
```

```
SOLUTION FOR FLOW HEADING  120.0000          CONVERGED IN    9   CYCLES
         LEG DIAMETER    =    0.18298E 01
         MAX HOR  FORCE  =    0.38571E 05
         MAX VERT FORCE  =    0.35867E 05

HEADING TO C.G.  =  119.5000
SHIPS HEADING    =  353.5925

C.G. COORDINATES =   -0.24621E 03    0.43818E 03

SHIPS LOAD COMPONENTS =   -0.49234E 04    0.17000E 05   -0.89824E 06

REFERENCE DATA FOR SLACK MOOR

HORIZONTAL DISTANCE FROM SURFACE POINT TO ANCHOR =    0.13258E 05

LENGTH OF CABLE ON BOTTOM =     0.95951E 03
INITIAL HORIZONTAL FORCE  =     0.32068E 05
WEIGHT PER UNIT LENGTH    =     0.48213E 01

ANCHOR LOCATIONS
LEG       X               Y
 1   -0.67690E 04    0.11492E 05
 2   -0.67690E 04   -0.11492E 05
 3    0.68290E 04   -0.11492E 05
 4    0.68290E 04    0.11492E 05
```

```
SOLUTION FOR FLOW HEADING  130.0000          CONVERGED IN    8   CYCLES
         LEG DIAMETER   =   0.18041E 01
         MAX HOR  FORCE =   0.37493E 05
         MAX VERT FORCE =   0.36987E 05

HEADING TO C.G. =  126.5000
SHIPS HEADING   =  353.6148

C.G. COORDINATES =   -0.29741E 03    0.40193E 03

SHIPS LOAD COMPONENTS =   -0.57420E 04    0.15273E 05   [illegible]E 06

REFERENCE DATA FOR SLACK MOOR

HORIZONTAL DISTANCE FROM SURFACE POINT TO ANCHOR =   0.[illegible] 05

LENGTH OF CABLE ON BOTTOM =     0.95416E 03
INITIAL HORIZONTAL FORCE  =     0.31207E 05
WEIGHT PER UNIT LENGTH    =     0.46867E 01

ANCHOR LOCATIONS
LEG         X             Y
 1   -0.67705E 04    0.11494E 05
 2   -0.67705E 04   -0.11494E 05
 3    0.68305E 04   -0.11494E 05
 4    0.68305E 04    0.11494E 05
```

FINAL DESIGN RESULTS

```
CRITICAL FLOW HEADING         :    110.0000
MAXIMUM LEG DIAMETER          :    0.1843[illegible]E 0[illegible]
MAXIMUM HORIZONTAL FORCE      :    0.3[illegible]15[illegible]E 0[illegible]
MAXIMUM VERTICAL FORCE        :    0.3[illegible]22[illegible]E 0[illegible]
MAXIMUM CABLE UNIT WEIGHT     :    0.4893[illegible]E 0[illegible]
```

LETTER REPORT NO. 5

DEVELOPMENT OF A SELECTION METHOD FOR MOOR COMPONENTS
(WORK PACKAGE 1, TASK 4)

CONTRACT NUMBER N62477-76-C-0002

BY: R. L. Webster

3 MARCH 1976

Electronics Systems Division
The General Electric Company
Syracuse, New York 13201

This Letter Report is submitted in compliance with item no. (5) of the Milestones and Deliverables Schedule of Contract N62477-76-C-0002 dated 17 June 1975 as revised 4 August 1975.

TABLE OF CONTENTS

INTRODUCTION

This Letter Report describes the procedure used in the selection of mooring system components other than mooring legs. Those components which were assumed to be available for selection in this effort are:

1 - Anchors

2 - Chain Assemblies

3 - Hawser Lines

4 - Riser Buoys

In general, the procedures described in NAVFAC Design Manual 26 (Chapters 6 and 7) were employed. The procedures used and limitations, where they exist, are described in the following discussion. A flow chart of the procedures is given in Figure 5-1 and a description of the input required for the combined DSSM static design program is included at the end of this report. The combined program will be delivered to the David Taylor Naval Ship Research and Development Center and placed on the computer there on 12 March 1976.

DISCUSSION

Interface with the Static Design Program

The DSSM static design program, which was described in Letter Report No. 4, estimates the size of the mooring legs and the maximum mooring leg loading for either a slack catenary or a neutrally buoyant taut moor. The maximum loading data provide the information required for component selection. Once this data is obtained, the program continues on to select the components. To enable the selection, the input description of the mooring legs includes a set of integers which are coded to identify the type of anchor, buoy and hawser desired. These integers correspond to entries in tables of component characteristics which have been generated and included in a special subroutine. This subroutine is essentially a set of FORTRAN DATA statements which list the component inventory. This inventory is based primarily on the standard components listed in DM-26 Chapter 7 plus a major portion of the catalog of marine and industrial braided ropes available from Samson Cordage Works, Boston, Ma. The contents of this inventory are listed at the end of this report, and the

types of components included are discussed in the following sections.

It was necessary to assume a set of units in the generation of the inventory. Up to this point the program has assumed no specific set of units and implied the units only through the input of a consistent set of data. It would be possible to continue this approach by requiring the input of the inventory in a manner similar to that used for describing the ship load tables. However, this was felt to be too awkward. Should a different set of units be desired or if modifications and/or additions to the tables are needed, the subroutine can be modified relatively easily. The assumed units are as follows:

Buoy dimensions - feet

Weights (in air) - pounds

Hawser Diameters and chain sizes - inches

Anchor Selection Procedure

The following anchor types are available in the inventory:

1 - Standard stockless anchors with stabilizers (Table 7-17 of DM-26 page 7-25)

2 - NAVSHIP lightweight anchors (Table 7-16 of DM-26 page 7-24)

3 - NAVFAC STATO anchors (Table 7-18 of DM-26 page 7-26)

It is recognized that for many applications an imbedment anchor is more appropriate than any of the above, however, there is not sufficient design data available to develop any inventory data. The procedures do assume that an imbedment anchor may be specified, and in that case the program will acknowledge that an imbedment anchor has been selected and will output the loads the anchor must support. The program also recognizes the specification of a mushroom and a stock (Admiralty) anchor; however, there is no inventory data available for these.

Each of the anchor types except the imbedment anchor requires the specification of a holding power function and a bottom condition factor to determine the required weight of the anchor. The two tables on page 6-45 of DM-26 are used for this purpose. The holding power functions relate the anchor holding

power in firm sand to the in-air weight of the anchor. These functions are listed below:

ANCHOR TYPE	HOLDING POWER
Navy Standardy stockless with stabilizers	7 Wa
NAVSHIP Lightweight	$65\ (Wa)^{0.82}$
NAVFAC STATO	20 Wa
Stock (Admiralty)	7 Wa
Mushroom	2.5 Wa

where

Wa = anchor weight in air

The bottom condition factors suggested by DM-26 are:

TYPE OF BOTTOM	FACTOR
Compacted Sand	1.0
Stiff dense clay (plastic)	1.5
Sticky clay of medium density (cohesive)	2/3
Soft mud (fluid), loose coarse sand, gravel	1/3
Hard bottom (rock, shale, boulders) (use only Navy Standard stockless)	1/4
Mud bottom with NAVFAC STATO	3/4

The program allows input of this bottom condition factor or it will select one of the above factors based on an input integer denoting the bottom type. The required anchor weight is then determined from the maximum horizontal force found in the design iterations and the holding power function multiplied by the bottom condition factor. For those anchor types included in the inventory, the anchor which has a weight exceeding the required weight is then selected. If there is no inventory or if the inventory does not contain a large enough anchor the program will print the required anchor weight with a message. If a satisfactory anchor is found in the inventory, the anchor type, weight and Federal stock no. will be printed.

The only anchor included in the program that is appropriate for use with taut moors is the imbedment anchor. Therefore, when taut moors are specified the anchor selection procedure degenerates to the output of the maximum loading the imbedment anchor must support.

Selection Procedure for Chain Assemblies

The static design program is not sufficiently general to allow for detailed design of a system with a combination of mooring leg materials (e.g., a leg partly made of synthetic rope and partly made of chain). However, where fishbite is a problem or where the moor may experience considerable interaction with the bottom it is customary to use chain for a portion of the mooring leg. Although the design does not deal explicitly with the combined effects in such a situation it is felt advisable to estimate the size of chain that would be required to support the maximum loads obtained in the design process. For this reason the inventory includes the table of stud link cast steel chains contained in Table 7-9 of DM-26 (page 7-18). The inventory lists the chain diameter, breaking strength and weight per unit length in air.

Two computations are available for chain selection. The first one estimates the chain size required to develop the anchor holding power on slack moors. In those instances where a specific anchor is not selected, then the chain is selected to resist the maximum horizontal load. The second case selects a chain size to support a given length of chain in addition to the maximum tension load determined in the design iterations. The factor of safety specified for the design iterations is assumed in the chain strength calculation. The second calculation is available for both slack and taut moors while the first applies only to slack moors. It should be emphasized that the selection procedure is approximate and the actual behavior of the combined mooring system including the chain, etc., should be evaluated by further analysis (e.g., SEADYN).

Hawser Selection Procedure

In the situation where a slack moor calls for a hawser, the program assumes it is essentially of fixed length and it must support the maximum horizontal force from the mooring leg plus the weight of the hawser in air. The safety factor specified for the mooring leg design is assumed to apply. The inventory contains entries for the four types of marine and industrial braided ropes available from Samson Cordage Works, Boston, Ma. Specifically, they are:

Samson 2-in-1 ® Braided Nylon

Samson 2-in-1 ® Power Braid

Samson 2-in-1 ® Stable Braid

Samson Blue Streak Single Braid

The inventory lists the diameter, type, breaking strength, and weight per 100 ft. The diameters included in the inventory are 1/2 in., 3/4 in., and all of the available diameters from 1.0 in. to 5.0 in. The data used is based on Samson Cordage Works publication UM-SWS 2/72 CP5M.

Riser Buoy Selection Procedure

Riser buoys may be specified as part of a slack mooring system. If a riser buoy is to be used, it is required to support the maximum vertical component of the mooring leg loading plus the weight of the length of chain selected plus half of the hawser weight. The inventory provided in the program contains the six bar riser chain-type buoys from Tables 7-1 and 7-2 of DM-26 (pages 7-27 and 7-28). These are cylindrical buoys and are the only ones considered as stock items at present. The inventory tables for these buoys include the diameter, height, air-weight, Federal Stock No., and an assumed nominal value and upper bound for the buoyant force delivered by the buoy. The nominal (or lower) buoyant force is calculated based on the assumption that 2/3 of the buoy height is submerged. The upper bound assumes there is one foot of buoy freeboard. In two cases there is an overlap of buoyant force range for the six buoys in the inventory. In selecting the buoy, the buoys are checked in ascending nominal force order. When one is found which has a nominal buoyant force which exceeds the maximum vertical force, then the upper bound is checked from the previous buoy in the table. If that force exceeds the maximum vertical force, then the

previous buoy is selected. Otherwise, the selected buoy is the one with the nominal force exceeding the maximum vertical force.

The program recognizes the possibility of specifying a buoy other than those in the inventory. This may occur either by requiring a large buoyant force or by indicating a nonstandard buoy in the input. In either case the program will simply print the buoyant force required.

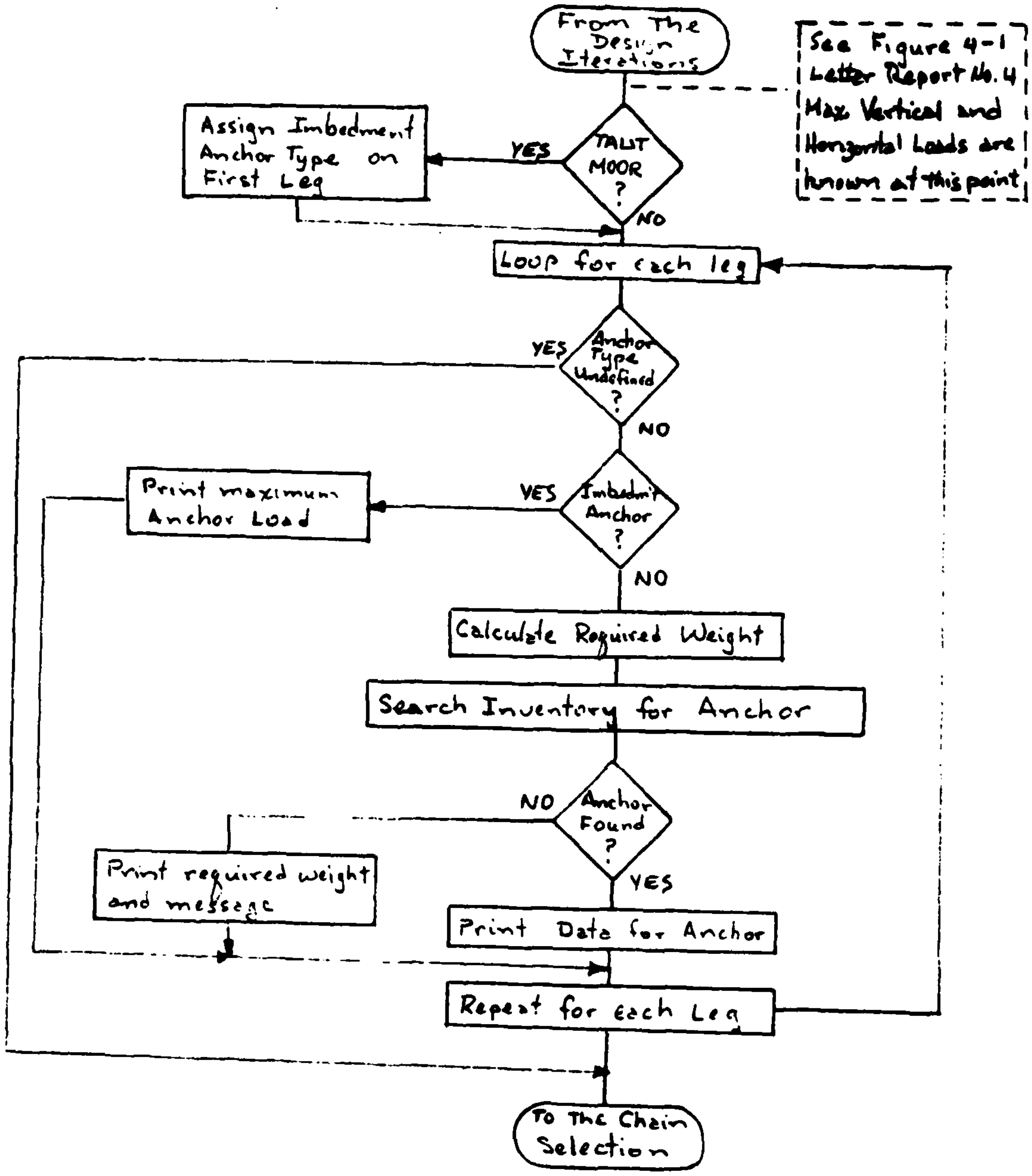


Figure 5-1. Logic Flow Chart for Component Selection

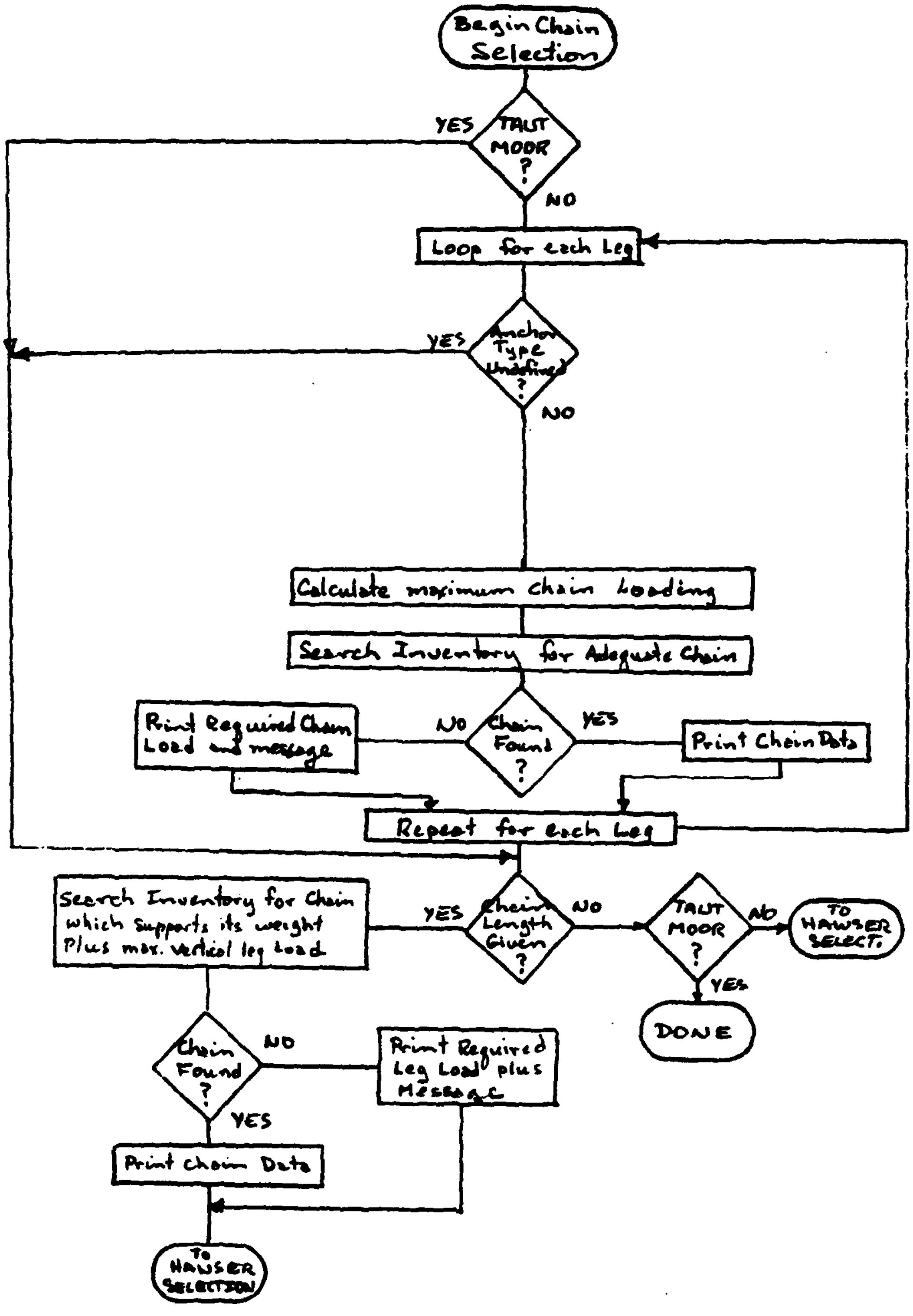


Figure 5-1. Logic Flow Chart for Component Selection (Continued).

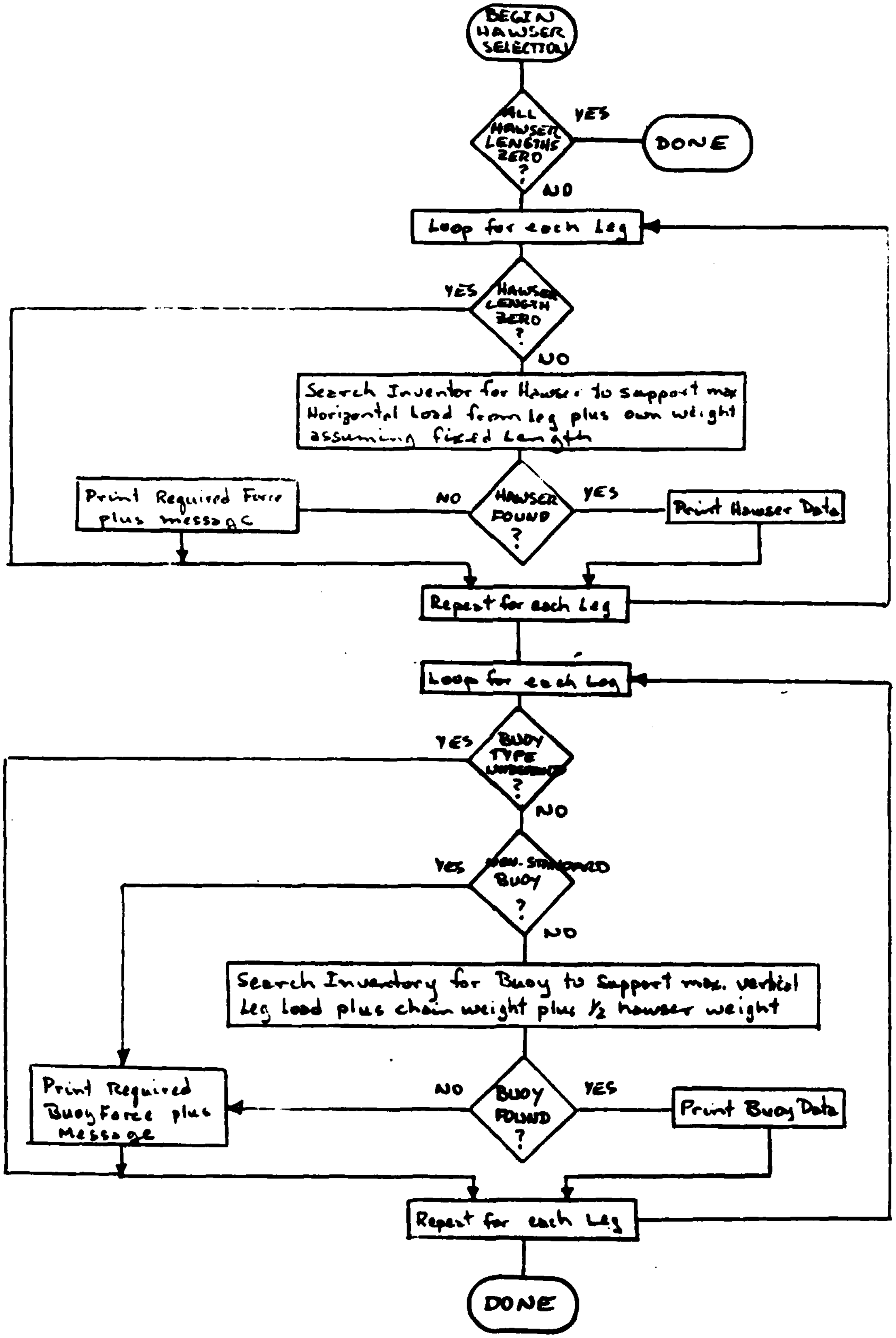


Figure 5-1. Logic Flow Chart for Component Selection (Continued)

C O M P O N E N T   I N V E N T O R Y

ANCHOR TYPE = NAVY STD STOCKLESS

WEIGHT	FED. STOCK NO.	HOLD. POWER (FIRM SAND)
0.30000E 04	C2040-516-7758	0.21000E 05
0.50000E 04	C2040-516-7757	0.35000E 05
0.60000E 04	C2040-516-7756	0.42000E 05
0.70000E 04	C2040-516-7755	0.49000E 05
0.90000E 04	C2040-516-7754	0.63000E 05
0.10000E 05	C2040-272-2244	0.70000E 05
0.13000E 05	C2040-272-2245	0.91000E 05
0.14500E 05	C2040-272-2246	0.10150E 06
0.18000E 05	C2040-516-7753	0.12600E 06
0.20000E 05	C2040-272-2247	0.14000E 06
0.25000E 05	C2040-272-2242	0.17500E 06
0.30000E 05	C2040-272-2243	0.21000E 06
0.40000E 05	C2040-277-2423	0.28000E 06

ANCHOR TYPE = NAVSHIP(LWT)

WEIGHT	FED. STOCK NO.	HOLD. POWER (FIRM SAND)
0.10000E 03	H2040-377-8500	0.28374E 04
0.15000E 03	H2040-377-8501	0.39565E 04
0.20000E 03	H2040-377-8502	0.50091E 04
0.30000E 03	H2040-377-8503	0.69848E 04
0.50000E 03	H2040-377-8504	0.10619E 05
0.75000E 03	H2040-377-8505	0.14807E 05
0.10000E 04	H2040-377-8506	0.18746E 05
0.15000E 04	H2040-377-8507	0.26140E 05
0.20000E 04	H2040-377-8508	0.33095E 05
0.25000E 04	H2040-377-8509	0.39740E 05
0.30000E 04	H2040-377-8510	0.46148E 05
0.40000E 04	H2040-377-8511	0.58426E 05
0.50000E 04	H2040-378-5533	0.70137E 05
0.60000E 04	H2040-378-5534	0.81470E 05
0.10000E 05	H2040-377-8512	0.12385E 06
0.13000E 05	H2040-377-8513	0.15358E 06

ANCHOR TYPE = NAVFAC STATO

WEIGHT	FED. STOCK NO.	HOLD. POWER (FIRM SAND)
0.20000E 03	2CF2040-800-9659	0.40000E 04
0.30000E 04	2CF2040-702-7564	0.60000E 05
0.60000E 04	2CF2040-702-6785	0.12000E 06
0.90000E 04	2CF2040-702-6786	0.18000E 06
0.12000E 05	2CF2040-702-6787	0.24000E 06
0.15000E 05	2CF2040-801-7938	0.30000E 06

[illegible]-LINK CHAIN

SIZE	STRENGTH	WEIGHT/LENGTH
[illegible]	48550.	5.5556
[illegible]	65280.	7.7778
1.0000	84500.	9.4444
1.1250	106080.	12.2222
1.2500	130070.	15.0000
1.3750	156330.	17.7778
1.5000	185060.	21.1111
1.6250	216030.	24.4444
1.7500	249210.	29.3333
1.8750	284540.	32.7778
2.0000	322000.	36.6667
2.1250	361530.	41.1111
2.2500	403100.	46.6667
2.3750	446550.	51.6667
2.5000	492190.	57.7778
2.6250	539520.	63.3333
2.7500	588930.	70.0000
2.8750	640070.	76.6667
3.0000	693000.	83.3333
3.1250	747580.	91.1111
3.2500	804070.	98.3333
3.3750	862130.	106.1111
3.5000	921810.	114.4444
3.6250	983080.	122.7778
3.7500	1045900.	131.1111
3.8750	1110210.	140.0000
4.0000	1176000.	148.8889
4.1250	1234200.	153.8889
4.2500	1311790.	170.0000
4.3750	1381330.	183.8889
4.5000	1452930.	198.3333

HAWSER DATA

SIZE	2-IN-1 NYLON STRENGTH	2-IN-1 NYLON WEIGHT/100L	2-IN-1 POWER BRAID STRENGTH	2-IN-1 POWER BRAID WEIGHT/100L	2-IN-1 STABL BRAID STRENGTH	2-IN-1 STABL BRAID WEIGHT/100L	12 ST. BLUE STREAK STRENGTH	12 ST. BLUE STREAK WEIGHT/100L
0.5000	8300.	5.50	7300.	5.90	7500.	7.90	6300.	6.40
0.7500	18000.	15.00	16000.	13.00	16000.	18.00	13800.	14.00
1.0000	31300.	25.00	28400.	24.00	28400.	32.00	23500.	25.00
1.0625	36500.	31.50	33200.	29.00	33200.	37.00	0.	0.
1.1250	42000.	35.00	38000.	32.00	38000.	43.00	31500.	33.00
1.2500	47700.	41.00	43500.	37.00	43500.	49.00	36000.	38.00
1.3125	54000.	47.50	49000.	42.00	49000.	56.00	40600.	44.00
1.5000	57500.	63.00	61400.	55.00	51400.	71.00	50300.	55.00
1.6250	32600.	74.00	75000.	65.00	75000.	88.00	52200.	68.00
1.7500	99000.	89.00	90000.	81.00	90000.	106.00	74400.	82.00
2.0000	117000.	105.00	106000.	95.00	105000.	126.00	89000.	99.00
2.1250	135000.	124.00	124000.	111.00	124000.	148.00	102000.	115.00
2.2500	156000.	144.00	142000.	127.00	142000.	172.00	117000.	134.00
2.5000	178000.	165.00	162000.	143.00	152000.	197.00	134000.	153.00
2.6250	202000.	185.00	183000.	163.00	193000.	224.00	151000.	175.00
2.7500	225000.	212.00	205000.	193.00	205000.	253.00	170000.	197.00
3.0000	252000.	235.00	229000.	215.00	229000.	284.00	190000.	222.00
3.2500	308000.	294.00	280000.	253.00	230000.	350.00	232000.	274.00
3.6250	359000.	355.00	336000.	313.00	335000.	424.00	278000.	332.00
4.0000	436000.	423.50	396000.	377.00	395000.	504.00	327000.	395.00
4.2500	534000.	497.00	461000.	444.00	451000.	592.00	391000.	463.00
4.6250	536000.	575.00	531000.	515.00	531000.	686.00	439000.	537.00
5.0000	656000.	662.00	606000.	592.00	605000.	789.00	500000.	617.00

BUOY DATA

BUOY TYPE = BAR RISER CHAIN

O. D.	HEIGHT	WEIGHT	NOM. BUOYANCY	MAX. BUOYANCY	FED. STOCK NO.
6.33125	4.37500	2200.	4053.	5336.	02050-223-3657
7.37500	5.37500	2500.	7296.	9461.	02050-264-4497
9.50000	5.00000	7700.	7420.	10445.	02050-223-3655
10.50000	6.50000	9600.	14414.	20379.	02050-223-3652
10.50000	7.50000	10100.	17638.	25921.	02050-264-4498

LETTER REPORT NO. 6

DEFINITION OF DESIGN PARAMETER INPUTS FOR THE DSSM DYNAMIC ANALYSIS

(Work Package 2, Task 1)

CONTRACT NUMBER N62477-76-C-0002

By: R.L. Webster

12 May 1976

ELECTRONICS SYSTEMS DIVISION
THE GENERAL ELECTRIC COMPANY
SYRACUSE, NEW YORK 13201

This Letter Report is submitted in compliance with item no. (6) of the Milestones and Deliverables Schedule of Contract N62477-76-C-0002, dated 17 June 1975 as revised 4 August 1975.

INTRODUCTION

The purpose of this report is to describe the input information required by the DSSM dynamic analysis and to present the rationale used in selecting these inputs.

The dynamic analysis portion of the DSSM Computer Program has as its objective the estimation of the dynamic effects of an arbitrary sea state on the moored ship and the mooring components. It is specifically intended that the ability to treat the effects of the steady-state portion of the second order wave induced drift forces be included in the program.

The function of the program is primarily analysis or design evaluation rather than design definition. Thus it is presumed that a candidate moor design has been identified and an estimate of the dynamic response of the system to a specific set of sea conditions is desired. Of course, the program could be used in the customary open-loop design procedure of analyze-modify-re-analyze. Specifically eliminated from this effort, however, is any attempt to include some form of closed-loop design iterations.

During the execution of Work Package 1 it was found that some modification of the approach originally described in Letter Reports Nos. 1 and 2 was required. This involved the change from an implicit static design approach to an explicit one as described in Letter Report No. 4. The original approach was attempted since it was recognized that a static analysis capability would be required in order to provide a starting point for the dynamic analysis. The static design program developed in Work Package 1 is an effective preliminary design tool, but it does not provide an analysis capability nor does it allow for all of the detail required in a final moor design. This means that the development of a static analysis capability had to be included as part of Work Package 2.

Fortunately, the initial efforts on the implicit static design approach included much of the capability need. This was done within the framework of the SEADYN program. SEADYN was modified to allow the inclusion of a surface

ship and the specification of wind and current loading in essentially the same format as used in the static design program. The generality inherent in SEADYN for describing mooring legs, buoys and other components thus allows one to add significant detail to the mooring design identified in the DSSM static design program and proceed to a static analysis under a set of specified conditions. Unlike the static design program, the static analysis program determines the response of the system to the given loads with wind and surface currents assumed to be independently oriented. In addition the effects of arbitrary subsurface currents can be included. An option is provided which allows the direction of the wind and surface currents to be incrementally varied so that the excursion envelope can be traced.

The input parameters for the static analysis option are essentially those described in Letter Report No. 2, with the exception that leg lengths and diameters along with anchor locations are also input. The remainder of this report identifies the additional input parameters required to begin from a static configuration of the mooring system (i.e., the position of the ship and mooring components under the combined action of wind, currents and workloads) and add the dynamic wave effects induced by a random sea.

DISCUSSION

The method used in the dynamic analysis presumes that wave induced effects constitute small perturbations to the quasi-static steady-state configuration attained by the system under the action of a specific combination of the following effects:

1. Wind specified by speed and heading (relative to a global coordinate system).
2. Surface current specified by speed and heading.
3. Sub-surface current specified either as uniform velocity components (independent of depth) or as a spatially varying flow field described by a user-supplied subroutine (SEADYN format).
4. Point working loads located on the ship and/or various positions in the mooring or working system (e.g., end loads on a partially deployed array).
5. The steady-state portion of the second order wave induced drift force.

The last item in the list is not known a priori, and must be estimated by an iterative procedure which will be described in detail in the next Letter Report. It should be noted that the inclusion of this effect requires re-solving the static equations, thereby requiring the intimate coupling of the static and dynamic solutions. The SEADYN program offers a convenient framework to interface the dynamic and static solutions, thus it was decided to incorporate the DSSM dynamic analysis as an option within the SEADYN program.

The additional input required for the dynamic analysis can be described under three general headings:

1. Description of the Sea
2. Ship Response File
3. Option and Control Data

Each of these will be discussed briefly.

Description of the Sea

The traditional approach to describing random seas is through a spectral density function or a sea spectrum. The common methods for describing sea spectra were reviewed and it was determined that most of them can be described using two parameters. The general form of the most widely used spectra is

$$S(\omega) = A/\omega^5 \quad e^{-B/\omega^4} \tag{1}$$

By assigning appropriate values to A and B one can describe the Pierson-Moskowitz, the Bretschneider or the I.S.S.C. spectrum. Using the convention of Reference 1 where $S(\omega)$ represents $2\ h^2(\omega)$ (i.e., twice the square of the wave height) the values of A and B are given in the following table:

SPECTRUM	A	B
Pierson-Moskowitz	135	$9.7 \times 10^4/V_k{}^4$
Bretschneider's	$4200\ H_s{}^2/T_s{}^4$	$1050/T_s{}^4$
I.S.S.C.	$2760\ H_s{}^2/T_s{}^4$	$690/T_s{}^4$

where

V_k = wind speed (~~ft/sec~~ knots)

H_s = significant wave height (ft)

T_s = significant wave period (sec)

ω = the circular frequency (radians/sec)

The values shown are for the indicated dimensional units and the value of $S(\omega)$ is then in ft^2-sec.

The sea spectrum described by equation (1) assumes that the sea is a set of long crested waves with random amplitude, period and phase; therefore it describes uni-directional seas. It is possible to modify the spectrum to approximate short-crested or multi-direction seas (see Reference 2) but it would require

significantly more computation to estimate responses to such a spectrum since multiple headings must be treated for each sea state. At this point it appears that the uni-directional assumption is more conservative and much less costly to implement. Therefore, this effort will be limited to long-crested seas.

Reference 3 describes a modification of the spectrum to account for the interaction between the waves and the surface current. This effect is readily included and requires no additional input.

Ship Response File

The dynamic analysis assumes the regular wave responses and unit amplitude forcing functions for the ship are available on an auxiliary storage file in the format described in Reference 4. The file also contains tables for estimating the roll damping and steady state drift forces. This file is presumed to be generated by the DTNSRDC Ship Motion Program and it constitutes the only link between the two programs.

Option and Control Data

The control data for the dynamic analysis will be used to identify the wave headings and frequency range to be investigated, to specify optional paths in the analysis, and to identify which components are to be presented in the output.

One or more wave headings can be investigated in a single analysis. The input will consist of a list of the headings to be analyzed.

The frequency interval to be treated at each heading will be specified by a frequency increment, $\Delta\omega$, and a cut-off frequency, ω_{max}.

The only option in the analysis sequence under present plans is an optional deletion of the drift force iterations. If the iterations are requested, the static configuration of the system will be modified until two successive estimates differ less than a specified amount. That amount can be input or it

will be assumed by the program. The iterations can be deleted (i.e., no updates in the static configuration will be made) if an input flag is non-zero.

The dynamic analysis has the potential of producing large amounts of output if the response spectrum data for all of the nodes and elements are generated. Since much of this data may not be useful (there is usually a few critical components), the program will allow the user to specify which nodes and elements are to be investigated. These will be specified simply by listing the nodal component or element number for which the response spectra will be generated.

System of Units

The SEADYN program has been written in a dimensionally independent format which requires the user to input all data in a self-consistent set of units. It may not always be convenient to express all of the input in the units used by the DTNSRDC Ship Motion Program to generate the ship motion data file. A provision for inputting conversion factors for converting the ship motion data into the assumed SEADYN units will be made. This will simply be a set of constants for force, mass, length and time which will be multipliers for the ship motion data. If any value is input as zero or blank then the multiplier will be assumed to be 1.0 (i.e., the units are consistent).

REFERENCES

1. Michel, W.H., How to Calculate Wave Forces and Their Effects, OCEAN INDUSTRY, June 1967, pp. 49-54.

2. PRINCIPLES OF NAVAL ARCHITECTURE, Chapter IX.

3. Wu, S.C., excerpt from PhD thesis, page 23.

4. McCreight, W.R., Use of Hydrodynamic Coefficients from DTNSRDC Ship-Motions and Sea-Loads Computer Program, DTNSRDC TM15-75-29 and related notes.

LETTER REPORT NO. 7

DESCRIPTION OF THE APPROACH TAKEN IN THE DYNAMIC SHIP-MOOR ANALYSIS

(Work Package 2, Task 2)

CONTRACT NUMBER N62477-76-C-0002

By: R.L. Webster

28 May 1976

Electronics Systems Division
The General Electric Company
Syracuse, New York 13201

This Letter Report is submitted in compliance with Item No. (7) of the Milestones and Deliverables Schedule of Contract N62477-76-C-0002, dated 17 June 1975 as revised 4 August 1975.

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INTRODUCTION

The purpose of this report is to describe the analytical/numerical procedures used in the DSSM dynamic analysis. The primary assumption in the dynamic analysis is that the wave induced motions are small perturbations on a quasi-static configuration of the ship and mooring system. This assumption allows the use of linear analysis techniques once the quasi-static configuration is determined. The process of linearizing the motion equations leads to frequency dependent terms which are most readily dealt with by frequency domain solution methods. Therefore, the essential elements of the DSSM dynamic analysis are:

1) A consistent modeling technique which describes the combined effects of the ship and moor,

2) A nonlinear static solution procedure which can be used to estimate the quasi-static configuration,

3) A linearization scheme to obtain the frequency domain equations,

4) A solution procedure for obtaining and combining the dynamic responses for the various frequencies of interest.

Each of these aspects of the DSSM dynamic program will be treated in the following discussion.

The overall dynamic solution procedure is summarized in flow chart form in Figures 7-1 and 7-2.

It is significant to note that the objectives of the DSSM dynamic analysis have been met entirely within the format of the SEADYN program. Thus instead of having a mooring analysis program with combined static and dynamic capability augmented by a cable analysis program (as envisioned in the work statement). This effort integrates the two programs. This approach has some distinct advantages since it simplifies program maintenance and reduces the requirements on the program users.

DISCUSSION

Modeling the Ship and Moor

The complete deep sea moor is a very complex system composed of a ship, mooring lines, buoys, floats, anchors and weights. Since it is desired to model as much of the detail as is economically and analytically feasible, a very general modeling procedure is required. The variety of mooring arrangements and the possible physical complexity of the moor discourage the use of continuous or distributed analytical models, and some form of discrete element model appears mandatory.

The discrete element approach used in the DSSM dynamic analysis can be viewed as a combination of the finite element method and the lumped parameter method. The ship, buoys, anchors and other large bodies are modeled as lumped masses and their governing equations are described in terms of the motion of a single point. The mooring lines, hawsers, etc., are represented via the finite element method as a system of straight elements with negligible bending and torsion resistances.

The general form of the equations of motion for a system which is modeled in terms of the motion of a set of discrete points is

$$[M]\,\{\ddot{u}\} + [C]\,\{\dot{u}\} + [K]\,\{u\} = \{f\} \qquad (1)$$

where

$\{u\}$, $\{\dot{u}\}$, $\{\ddot{u}\}$ represent the displacements, velocities, and accelerations of the set of points (nodes) used to model the system.

$[M]$ is a matrix representing the mass of the system

$[C]$ is a damping matrix

$[K]$ is a stiffness matrix

$\{f\}$ is a set of nodal point forces which represent the external loads applied to the system.

In nonlinear systems such as a moored ship each of the matrices and the applied forces are functions of the displacements and/or their derivatives. Solution of such a system of nonlinear differential equations is very difficult and in some cases explicit expressions for the coefficients may not be available. A common approach to the problem is to introduce a linearization by considering a small excursion from a known reference state. This procedure leads to an incremental form of the motion equations:

$$
\begin{aligned}
&[\tilde{M}]\,\{\Delta\ddot{u}\} + [\tilde{C}]\,\{\Delta\dot{u}\} + [\tilde{K}]\,\{\Delta u\} = \{\Delta f\} \\
&\{u\}_{t+\Delta t} = \{u\}_t + \{\Delta u\}
\end{aligned}
\qquad (2)
$$

In this form, the coefficient matrices and the load increments are functions of the "known" state at the beginning of the increment and are constant over the interval, Δt. It should be emphasized that this is an approximation and its validity is dependent on the size of $\{\Delta u\}$.

The incremental equations for the point used to represent the ship can be expressed as

$$[M_S + M_{AS}]\,\{\ddot{u}_S\} + [C_S]\,\{\dot{u}_S\} + [K_S]\,\{u_S\} = \{f_S\} \qquad (3)$$

where

- $\{u_S\}$ etc., represent the six components of ship's motion (surge, sway, heave, roll, pitch, yaw)
- $[M_S]$ is the ship's mass matrix
- $[M_{AS}]$ is the added mass due to fluid acceleration
- $[C_S]$ is the equivalent linearized damping matrix
- $[K_S]$ is the ship's hydrostatic restoring matrix or stiffness matrix
- $\{f_S\}$ is a set of point equivalent forces representing the wave excitating forces.

In order to obtain this linearization it is usually assumed that the ship is driven by a simple harmonic wave. With this assumption, the added mass and damping are dependent on the wave frequency. In addition, the viscous roll damping is a function of the roll amplitude. Equations of this form can be obtained for slender bodies using strip theory. For more general bodies a more general theory is required. The DSSM program presumes that the coefficients in the linearized ships motion equation are calculated external to the program and provided on an auxiliary storage device (magnetic tape, disc file, etc.). It is presumed at this point that the ship's motion file is generated by the DTNSRDC Ship Motion Program, which uses the strip theory approach. It should be noted, however, that no direct coupling between the two computer programs exists and that the coefficients could be determined by some other means as long as they are stored in the format expected by the DSSM program. Details of that format will be given in the final documentation.

The straight line element used to represent the mooring and hawser lines is a simple tension element. It assumes the behavior of the element is fully described by the movement of its two end points (nodes). A linear interpolation function is assumed for the displacement between the nodes. The mass of each element may be treated by a simple lumping procedure (1/2 of the mass assigned to each node) or by the consistent mass approach which uses the linear interpolating functions. The program provides an option to use either form of the mass matrix. In either case, the lumped form is used for the fluid added mass.

Specific details of the element formulation and the equation assembly procedures will not be given here, but they are readily available in the open literature of the finite element method. A brief summary of the equations for the straight element is given in Appendix I, and the detailed development will be provided in the final documentation of this contract.

The final assembled system of equations representing the motion of the mooring system can be written

$$[M_M]\{\ddot{u}_M\} + [C_M]\{\dot{u}_M\} + [K_M]\{u_M\} = \{f_M\} \qquad (4)$$

where

$\{u_M\}$, $\{\dot{u}_M\}$, $\{\ddot{u}_M\}$	represent the incremental displacements, velocities, and accelerations of the nodal points used to model the moor
$[M_M]$	is the mooring mass matrix which includes fluid added mass
$[C_M]$	is the mooring damping matrix
$[K_M]$	is the mooring incremental stiffness matrix
$\{f_M\}$	is a set of incremental nodal forces applied to the moor.

The effects of lumped bodies such as subsurface buoys, anchors or sinkers not on the bottom, or other suspended components are assumed to be located at a node. The mass of each body is added to the appropriate diagonal component of the mass matrix and the weight/buoyancy and any flow drag effects are added to the force vector.

The damping matrix can be considered to be composed of two separate effects. First is the internal damping from the mooring lines, etc. This effect is modeled in the DSSM program by assuming the damping matrix is proportional to the mass and/or the stiffness matrices with the proportionality constants given in the input. The remaining portion of the damping matrix comes from the fluid resistance to the motion of the moor. Strictly speaking, this resistance is a nonlinear function of the relative velocity between the cable (or body) and the fluid. This effect is linearized by assuming that the ocean currents contribute only to the static configuration and that the motions about that reference are small. The fluid damping is then linearized by deriving a linear coefficient for the nodal velocity which dissipates the same energy as that dissipated by the nonlinear damping in one cycle at a given frequency. This linearization procedure is described in more detail in Appendix II.

Anchors on the bottom are treated as fixed points in the system. In some cases the mooring system may contain sinkers or anchors near the bottom. In the process of the static solution, the status of these bodies is checked to see if they are at the bottom or lifted off and the calculations are altered accordingly.

The moor may employ buoys at the surface. These also are treated as lumped bodies but they require more detailed treatment than a subsurface buoy. It has been necessary to develop motion equations for the surface buoys to account for the effects of surface currents, winds and waves. The form of the equations is

$$[M_{SB}]\ \{\ddot{u}_{SB}\} + [C_{SB}]\ \{\dot{u}_{SB}\} + [K_{SB}]\ \{u_{SB}\} = \{f_{SB}\} \tag{5}$$

where

$\{u_{SB}\}$ represents the six components of incremental motion of the buoy

$[M_{SB}]$ is the mass matrix for the buoy (including added mass of the fluid)

$[C_{SB}]$ the linearized damping matrix for the buoy

$[K_{SB}]$ is the linearized hydrostatic restoring matrix for the buoy

$\{f_{SB}\}$ is a set of driving forces

The DSSM program calculates the terms in the buoy motion equations for a harmonic wave input. In addition the steady effects of wind and surface current are included in the static solution. The buoy equations are given in Appendix III.

Combining the equations for ship, moor, and surface buoys requires some special manipulations. The ship and buoy equations are written to describe the motion of a single point in the body in terms of six degrees of freedom. The mooring equations are written in terms of the three displacement degrees of freedom at each of the points where the moor connects to the bodies. Assuming the ship (or buoy) is a rigid body the displacement of any point on the body can be obtained in terms of the six components of motion of one point from the following relation:

$$\{u_p\} = \left[\begin{array}{ccc|ccc} 1 & 0 & 0 & 0 & \Delta z & -\Delta y \\ 0 & 1 & 0 & -\Delta z & 0 & \Delta x \\ 0 & 0 & 1 & \Delta y & -\Delta x & 0 \end{array}\right] \left\{\begin{array}{c} \{u_o\} \\ --- \\ \{\theta_o\} \end{array}\right\} \qquad (6)$$

where

$\{u_p\}$ are the three components of displacement at an arbitrary point on the rigid body

$\{u_o\}$ are the three components of displacement at the reference point

$\{\theta_o\}$ are the three components of rotation at the reference point

Δx, Δy, Δz are the components of distance between the two points measured from 0 to p (i.e., $\Delta x = x_p - x_o$, etc.)

Equation (6) allows one to write the equations of motion at the point where the moor is attached in terms of the movement at the body reference point.

The process of assembling the equations for the combined system requires the use of coordinate transformations. The equations for each component are derived in a local coordinate system which may vary from component to component. For example, the ship's motion equations are expressed in a form which assumes the x axis is from fore to aft, the y axis is to the port side, and the z axis is up. Each cable element assumes its x axis is along the element from the first node given to the second node. The element equations can be combined only after they have been transformed to a single global coordinate system. The form of the transformation is

$$\{\overline{u}\} = [T]\{u\} \qquad (7)$$

where

$\{\overline{u}\}$ are the nodal point displacement components associated with a particular element written in the local coordinate system.

{u} are the nodal displacements at the same points written in the global coordinate system

[T] is a transformation matrix involving direction cosines.

The general form of the motion equations for a single element expressed in the local coordinate system can be written

$$[\overline{M}]\,\{\ddot{\overline{u}}\} + [\overline{C}]\,\{\dot{\overline{u}}\} + [\overline{K}]\,\{\overline{u}\} = \{\overline{f}\} \qquad (8)$$

Applying the transformation (5) yields

$$[T]^T\,[\overline{M}]\,[T]\,\{\ddot{u}\} + [T]^T\,[\overline{C}]\,[T]\,\{\dot{u}\} + [T]^T\,[\overline{K}]\,[T]\,\{u\} = [T]^T\,\{\overline{f}\} \qquad (9)$$

This result has the same general form as the original equation. Equation (9) then represents the element motion equations in the global coordinate system.

The assembly process amounts to summing all of the effects of the elements of the system at each of the nodes. The general form of the assembled equations is not unlike the form for a single element. The only significant difference is the order of the system. The displacement vector, {u}, for the combined system contains entries for each degree of freedom at each node of the model.

The Static Solution Procedure

In the static analysis, the time dependent terms of (1) are dropped and one seeks the solution to a set of simultaneous equations of the form

$$[K]\,\{u\} = \{f\} \qquad (10)$$

For the mooring case the stiffness matrix, [K], is a function of the total displacement, {u}, as well as the load level (nonlinear materials). In addition, the applied loads will also be a function of the displacements since wind and current loads depend on the orientation of the body. Nonlinear solution techniques must be used to find the final configuration of the system.

The SEADYN program provides various options for solving the nonlinear statics problem. The details of the various options will be described in the final documentation, and only a few general comments will be given here. The

most effective method in SEADYN is an incremental procedure which applies the loading in a series of steps and iterates at each step. The iterations take the form of a modified Newton-Raphson procedure. The solution begins with an estimate of the configuration of the system and a specification of the load level. The components of the load vector, the element forces, and the tangential stiffness matrix are calculated. The tangential stiffness matrix, $[\tilde{K}]$, gives the local slope of the load/displacement behavior and represents the first variation (or derivative) of the stiffness matrix of equation (10). The differences between the applied forces and the internal reaction are used to estimate the correction to the configuration by the following set of equations

$$\begin{aligned} [\tilde{K}]\ \{\Delta u\}_{i+1} &= \{f(u_i)\} - \{g(u_i)\} \\ \{u\}_{i+1} &= \{u\}_i + \{\Delta u\}_{i+1} \end{aligned} \qquad (11)$$

where

$f(u_i)$ are the nodal external forces in the configuration described by $\{u\}_i$

$\{g(u_i)\}$ are the nodal components of the internal reactions to the loads in the same configuration

The iteration is continued at each load level until successive estimates of $\{u\}$ are sufficiently close. The tangent stiffness estimate is not necessarily recalculated at each stage of the iteration. It is recalculated at specified intervals in an effort to reduce computation costs (hence the modification of the Newton-Raphson method). SEADYN treats the static load in two stages:

DEAD LOAD: the loading is the gravity/buoyancy effects of the system. No current, wind or work loads. This gives the quiescent configuration of the system.

LIVE LOAD: currents, wind, and work loads are applied to move the system from the configuration obtained in the dead load analysis.

During the LIVE LOAD analysis the loads on the mooring, ship, buoy, etc., are recalculated at each stage of the iteration to account for the effects of

changing orientation. The same options for describing the ship's loading as those used in the Static Design Program (Letter Report No. 3) are used in SEADYN. Wind and surface current effects on the surface buoys are treated with input drag coefficients. The calculations of the internal reactions take into account the nonlinear nature of the cable materials.

The Linearized Motion Equations

The motion equations in the incremental form (2) using the result of the static LIVE LOAD analysis as a reference are used to investigate the dynamic response. The basic assumption is that the dynamic effects are excited only by the actions of a set of harmonic waves. All other loadings (surface and sub-surface currents, wind and work loads) are assumed to contribute only to the attainment of the static reference state.

When the exciting force is a harmonic wave then the incremental force vector of equation (2) contains nonzero entries only at the positions corresponding to the nodes at the ship and the surface buoys. The entries for the ship are given by

$$[T_S]^T \{f_S\} \tag{12}$$

where $[T_S]$ is the local to global coordinate transformation matrix and $\{f_S\}$ are the ship forces from equation (3). These ship forces are of the form

$$\{f_S\} = \{F_S\}\, e^{i\omega t} \tag{13}$$

where

ω is the wave frequency (rad/sec)

$\{F_S\}$ is a set of complex force amplitudes

The ship motion file provides the values of $\{F_S\}$ versus wave frequency. The components of $\{F_S\}$ are calculated assuming the wave has the form

$$\eta(\omega) = \eta_0\, e^{i\omega t} \tag{14}$$

where η_0 is real.

The buoy driving forces will have the same form as the ship forces:

$$[T_{SB}]^T \{f_{SB}\} = [T_{SB}]^T \{F_{SB}\} e^{i\omega t} \tag{14}$$

In this case, however, the real and imaginary parts of the amplitude vector, F_{SB}, are selected to give the proper magnitude with a phase shift corresponding to the time of travel between the ship and the buoy.

The steady-state response of a linear system to a harmonic input has the form

$$\{\Delta u\} = \{U\} e^{i\omega t} \tag{16}$$

Therefore equation (2) can be written

$$(-\omega^2[\tilde{M}] + i\omega [\tilde{C}] + [\tilde{K}]) \{U\} e^{i\omega t} = \{F\} e^{i\omega t} \tag{17}$$

The steady-state response vector, {U}, is a complex vector. The magnitude of the response in each degree of freedom is given by

$$|U_i| = \sqrt{U_i U_i^*} \tag{18}$$

where U_i^* is the complex conjugate of the i^{th} component of {U}.

The phase shift between the incident wave and the response is given by

$$\phi_i = \mathrm{Tan}^{-1} \frac{\mathrm{Im}(U_i)}{R_e(U_i)} \tag{19}$$

A phase angle of zero corresponds to the response being in phase with the incident wave at the ship reference point.

The dynamic tension response in each cable element is obtained by adding the displacement increments to the nodal positions, recalculating the element tensions based on the new lengths, and subtracting the tensions in the static reference configuration.

The Frequency Domain Solution for Regular Waves

The response amplitudes, {U}, for a given frequency are obtained by solving the linear simultaneous algebraic equations represented by (17). The coefficient matrices for mass and damping must be recalculated for each frequency since the linearization procedure leaves them dependent on the wave frequency.

The damping terms present some further difficulty. In addition to being frequency dependent, the linearized viscous terms are dependent on the amplitude of the response. The ship's roll-damping depends on the roll angle, the buoy rotational damping depends on the rotation angle, and the cable and lumped body damping depend on the lateral displacement amplitudes. Thus it is seen that the incremental equations are not strictly linear.

An approximate procedure is introduced to deal with this problem. This involves iterative solutions of the equations (17) for each frequency. The first solution at a given frequency is calculated assuming a ship's roll angle. The roll angle obtained from the solution is then used along with the other pertinent response amplitudes to recalculate the damping terms and obtain another solution. This procedure is repeated until two successive estimates of ship's roll are within 1° of each other. It is assumed that buoy and cable damping are less important than ship's roll and are thus converged when the roll has converged. The response is then dependent not only on the wave frequency, but also on the wave amplitude. This means that it is not appropriate to assume a unit amplitude for a given wave frequency with the intent of obtaining a Response Amplitude Operator (RAO) for that wave. It is necessary to have the correct wave amplitude at each frequency. Therefore, the sea spectrum must be used in the calculation of the regular wave responses. Once the steady state response for a given wave frequency and amplitude is obtained, the RAO is estimated by dividing by the wave amplitude.

The Steady-State Wave-Induced Drift Forces

Whenever waves encounter a floating body there arises a set of forces which tend to move the body in the direction the wave is traveling. These forces are

often neglected since they are usually small in magnitude. These are the so-called second order wave-induced drift forces. They are generally slowly varying compared to the frequency of the incident wave; however, they have an average or steady-state component which may be significant enough to cause an adjustment of the static position of the ship. These forces are directionally dependent and are sensitive to the amplitude of the ship's response to the wave. The DTNSRDC Ship's Motion File provides a table of coefficients which can be used to estimate the steady-state drift forces after the ship's dynamic response is estimated. It should be noted that these forces do not estimate the dynamic effects, which are at a lower frequency than the incident wave.

It would be appropriate to use the steady-state drift forces to make adjustments to the static reference configuration for each wave. This would mean that an additional iteration for each wave would be called for. The purpose of this iteration would be to seek a convergent solution involving the static reference state and the ship's dynamic response. The two major drawbacks to this approach are the significant cost increase and the question of the superposition of the final results to estimate the response to random seas (each wave would have a different static reference). Therefore, it was decided to eliminate the iteration for adjusting the static reference for each wave and simply calculate the drift forces for the converged solution. The use of the drift forces from each wave in the superposition of the regular wave responses is described in the next section.

The Solution Procedure for Random Seas

The steady-state drift force effects on the static reference configuration are treated in an approximate manner by assuming the contributions from each of the regular waves are cumulative (linear superposition assumed). The combined drift effects are then treated as an additional static load on the ship and the static reference state is adjusted to balance this additional loading using the modified Newton-Raphson method. Two options are provided at this point. In the first, this updated static reference is used to estimate the final combined static and dynamic response, regardless of the magnitude of the drift induced

displacement. The second option will repeat the regular wave solution with the new static reference until the change in reference configuration is smaller than a specified amount. With this option the dynamic effects will not be added to the static reference results until a convergent static reference is attained. In the first option it is assumed (without checking) that the updated static reference will not change the dynamic response appreciably and the results are combined without iteration.

The superposition of the regular wave responses to represent the response to random seas follows the well established methods from the theory of random vibrations [2]. The sea is assumed to be uni-directional (long-crested) and is described in terms of a generalized spectral energy density function having the following form:

$$S(\omega) = A/\omega^5 \, e^{-B/\omega^4} \tag{20}$$

Letter Report No. 6 discussed this representation in some detail and gave some typical values for the parameters, A and B. The values given there assume the spectrum represents twice the square of the wave height.

The frequencies to be included in the set of regular wave calculations are determined by specifying a frequency increment, $\Delta\omega$, a lower bound ω_{min}, and and upper bound, ω_{max}. Regular wave responses are then calculated for

$$\begin{aligned} \omega_i &= \omega_{min} + \frac{1}{2}\Delta\omega + (i-1)\Delta\omega \\ \omega_i &< \omega_{max} \end{aligned} \tag{21}$$

At each frequency the incident wave height is determined from the sea spectrum by the following:

$$h(\omega_i) = \left(\frac{1}{2} S(\omega_i)\Delta\omega\right)^{1/2} \tag{22}$$

(Note that the wave height is twice the wave amplitude.) This wave height is then used to converge on a steady-state dynamic response using the methods described in the previous section.

Let $H(i\omega)$ represent the response of one of the quantities (nodal displacement component or element tension). The response spectral density of this quantity is then given by

$$S_x(\omega) = HH^* \; S(\omega) \tag{23}$$

The mean square of the response is

$$E[x^2] = \int_{-\infty}^{\infty} HH^* \; S(\omega)d \quad = \int_{-\infty}^{\infty} S_x(\omega)d\omega \tag{24}$$

This integral is evaluated numerically using the points obtained from each of the regular wave solutions. Thus

$$E[x^2] \approx \sum_{i=1}^{N} S_x(\omega_i)\Delta\omega \tag{25}$$

where N is the number of regular wave components used.

When the response quantities represent the dynamic excursions relative to the static reference state, then their expected values (i.e., their means) are zero. The magnitude of the response is then treated as a static part plus a dynamic part. The amplitude of the dynamic part is assumed to follow a Rayleigh distribution with a mean-square value which is a function of the area under the response spectrum curve. Assuming the sea spectrum used is based on double the square of the wave height, the mean-square of the response amplitude is the value obtained by equation (25) divided by eight. It is possible, then, to make statistical estimates of the maximum response by making statistical estimates of the dynamic part and adding them to the static values obtained in the updated reference configuration.

APPENDIX I

THE EQUATIONS FOR A STRAIGHT CABLE ELEMENT

Consider a single straight element which is defined by the position of two nodes (one at each end). Select a local coordinate system with the x axis extending from the first node to the second in the reference state. When the element is in its unloaded state it has a length of ${}^{0}L$. Assume the material constitutive relation has the form

$$ {}_{0}^{t}S = {}_{0}^{t}E \; {}_{0}^{t}\varepsilon \tag{I-1} $$

where

${}_{0}^{t}S$ is the 2nd Piola-Kirchhoff stress in the state at time (or load) designated by t.

${}_{0}^{t}\varepsilon$ is the Green's strain at state t

${}_{0}^{t}E$ is a nonlinear material modulus which may be a function of strain.

The incremental form of this constitutive relation can be written for a small strain increment, $\Delta_{0}^{t}\varepsilon$:

$$ {}_{0}^{t+\Delta t}S = {}_{0}^{t}S + {}_{0}^{t}E_{T} \; \Delta_{0}^{t}\varepsilon \tag{I-2} $$

where ${}_{0}^{t}E_{T}$ is the tangent modulus evaluated at state t.

Assuming the displacement at any position along the element is a linear function of the displacements of the nodes one can write

$$\{u\} = \begin{Bmatrix} u \\ v \\ w \end{Bmatrix} = \left[(1 - \frac{x}{{}^{R}L})\,[I_3] \;\vdots\; \frac{x}{{}^{R}L}\,[I_3] \right] \begin{Bmatrix} u_1 \\ v_1 \\ w_1 \\ \hdashline u_2 \\ v_2 \\ w_2 \end{Bmatrix} \tag{I-3}$$

$$= [N]\ \{q\}$$

where

$\{u\}$ represents the components of the displacement from the reference state where the element length is ${}^{R}L$.

$\{q\}$ represents the components of the nodal displacements

$[N]$ is a shape function matrix

$[I_3]$ is the identity matrix of order 3.

${}^{R}L$ is the element length in the reference state.

Equation (I-3) represents the finite element assumption for the displacement behavior.

The symbolic expression for the large displacement kinematic relations for movement from a reference state to some later position at t can be written

$${}^{t}_{R}\{\varepsilon\} = {}^{t}_{R}[D]\ {}^{t}_{R}\{u\} \tag{I-4}$$

Substitution from (I-3) yields

$${}^{t}_{R}\{\varepsilon\} = {}^{t}_{R}[D]\ {}_{R}[N]\ {}^{t}_{R}\{q\} = {}^{t}_{R}[B]\ {}^{t}_{R}\{q\} \tag{I-5}$$

Assuming that the Lagrangian strain increment, ${}^{t+\Delta t}_{t}\varepsilon$ is approximated by the Almansi strain increment, ${}^{t+\Delta t}_{t+\Delta t}\varepsilon$, it can be shown [2] that

$$ {}^{t}_{R}E_T = \frac{{}^{o}A}{{}^{R}A} \left(\frac{{}^{R}L}{{}^{o}L}\right)^3 {}^{t}_{o}E_T \tag{I-6} $$

where

${}^{o}A$, ${}^{R}A$ are the element cross-section areas in the unstrained and reference configurations, respectively.

Using these results with the second variation of the strain energy leads to the tangent stiffness matrix which can be written

$$ {}^{t}_{R}[K_T] = {}^{t}_{R}\left(\begin{bmatrix} k_o & -k_o \\ -k_o & k_o \end{bmatrix} + \begin{bmatrix} k_1 & -k_1 \\ -k_1 & k_1 \end{bmatrix} + \begin{bmatrix} k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} + \begin{bmatrix} k_G & -k_G \\ -k_G & k_G \end{bmatrix} \right) \tag{I-7} $$

where

$$ [k_o] = \frac{{}^{t}_{o}E_T \; {}^{o}A}{{}^{o}L} \left(\frac{{}^{R}L}{{}^{o}L}\right)^2 \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} $$

$$ [k_1] = \frac{{}^{t}_{o}E_T \; {}^{o}A}{{}^{o}L} \left(\frac{{}^{R}L}{{}^{o}L}\right)^2 \begin{bmatrix} 2\theta_1 & \theta_2 & \theta_3 \\ \theta_2 & 0 & 0 \\ \theta_3 & 0 & 0 \end{bmatrix} $$

$$ [k_2] = \frac{{}^{t}_{o}E_T \; {}^{o}A}{{}^{o}L} \left(\frac{{}^{R}L}{{}^{o}L}\right)^2 \begin{bmatrix} \theta_1\theta_1 & \theta_1\theta_2 & \theta_1\theta_3 \\ \theta_2\theta_1 & \theta_2\theta_2 & \theta_2\theta_3 \\ \theta_3\theta_1 & \theta_3\theta_2 & \theta_3\theta_3 \end{bmatrix} $$

$$ [k_G] = \frac{{}^{t}P}{{}^{t}L} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} $$

$$ \theta_1 = \frac{{}^{t}_{R}U_2 - {}^{t}_{R}U_1}{{}^{R}L} $$

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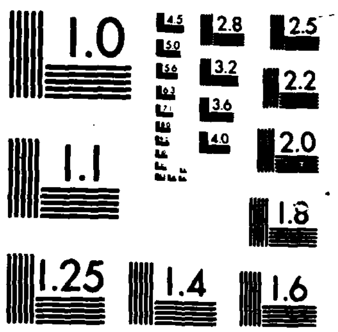

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$$\theta_2 = \frac{{}^t_R v_2 - {}^t_R v_1}{{}_R L}$$

$$\theta_3 = \frac{{}^t_R w_2 - {}^t_R w_1}{{}_R L}$$

${}^t P$ is the axial load in the element of state t.

If the variation of the applied loading with respect to the nodal displacements is neglected, then the incremental matrix at state t, $[\tilde{K}]$, can be approximated by the tangent stiffness, $[K_T]$.

The second variation of the kinetic energy with respect to the nodal displacements leads to an expression for the mass matrix. The result is [2]

$$[M] = \frac{{}_R\rho \; {}_R A \; {}_R L}{3} \begin{bmatrix} I_3 & 1/2 \quad I_3 \\ 1/2 \; I_3 & I_3 \end{bmatrix} \tag{I-8}$$

where

${}_R\rho$ is the material density in the reference state.

This form of the mass matrix is consistent with the assumption of the element shape function of equation (I-3). A diagonalized version of the mass matrix can be obtained by lumping the mass at the two nodes. The lumped mass matrix is then

$$[M]_{(\text{lumped})} = \frac{{}_R\rho \; {}_R A \; {}_R L}{2} \; [I_6] \tag{I-9}$$

A lumped approximation to the fluid added mass is

$$[M]_{(\text{fluid})} = \frac{C_M \, \rho_f \; {}_R A \; {}_R L}{2} \begin{bmatrix} 0 & & & & & \\ & 1 & & & & \\ & & 1 & & & \\ & & & 0 & & \\ & & & & 1 & \\ & & & & & 1 \end{bmatrix} \tag{I-9}$$

where

C_M is the added mass coefficient

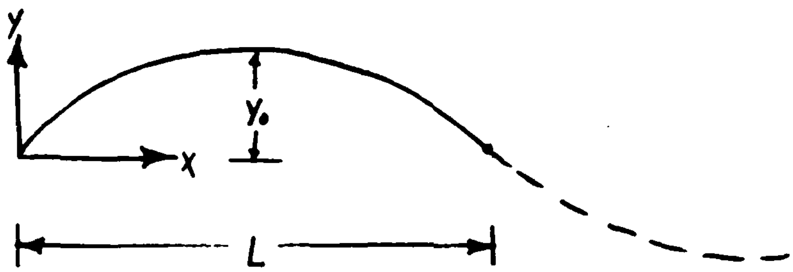
ρ_f is the fluid density

This form of the incremental added mass neglects the variation of the added mass with a rotation of the element.

APPENDIX II

LINEARIZATION OF THE FLUID DAMPING ON A CABLE

Assume the cable is oscillating harmonically in a transverse mode. Further assume that a typical segment of the cable takes the shape of a sine curve during the oscillation. Then equate the work done in one cycle with the nonlinear drag terms to the work done in one cycle of a linearized model.



$$y = y_o \sin \omega t \sin \frac{\pi x}{L}$$
$$\dot{y} = y_o\, \omega \cos \omega t \sin \frac{\pi x}{L} \qquad \text{(II-1)}$$

The nonlinear form of the normal drag force per unit length is

$$f_d = \frac{1}{2}\, \rho_f\, C_N\, d\, \dot{y}^2 \qquad \text{(II-2)}$$

where

C_N is the normal drag coefficient
d is the cable drag diameter

The linear model of this force is

$$\bar{f}_d = \bar{C}\, \dot{y} \qquad \text{(II-3)}$$

The work dissipated by the nonlinear drag in one cycle over the length L is

$$W = \oint \int_0^L f_d \, d_x \, d_y = \int_{-\frac{\pi}{2\omega}}^{\frac{\pi}{2\omega}} \int_0^L f_d \, dx \, \dot{y} \, dt$$

$$= \frac{1}{2} \rho_f C_N d \quad 2 \int_{-\frac{\pi}{2\omega}}^{\frac{\pi}{2\omega}} \int_0^L (\dot{y})^3 \, dx \, dt \tag{II-4}$$

The work dissipated by the linearized term is

$$\overline{W} = \oint \int_0^L \overline{C} \, \dot{y} \, dx \, dy = 2\overline{C} \int_{-\frac{\pi}{2\omega}}^{\frac{\pi}{2\omega}} \int_0^L (\dot{y})^2 \, dx \, dt \tag{II-5}$$

Equating the work terms yields

$$\overline{C} = \frac{\frac{1}{2} \rho_f \, C_N \, d \displaystyle\int_{-\frac{\pi}{2\omega}}^{\frac{\pi}{2\omega}} \int_0^L (\dot{y})^3 \, dx \, dt}{\displaystyle\int_{-\frac{\pi}{2\omega}}^{\frac{\pi}{2\omega}} \int_0^L (\dot{y})^2 \, dx \, dt} \tag{II-6}$$

Evaluating the integrals substituting from (II-1),

$$\int_{-\frac{\pi}{2\omega}}^{\frac{\pi}{2\omega}} \int_{0}^{L} (\dot{y})^3 \, dx \, dt = y_0^{\,3} \;\; \omega^3 \int_{-\frac{\pi}{2\omega}}^{\frac{\pi}{2\omega}} \cos^3 \omega t \, dt \int_{0}^{L} \sin^3 \frac{\pi x}{L} \, dx$$

$$= \frac{16 \; y_0^{\,3} \; \omega^2 \; L}{9 \; \pi} \tag{II-7}$$

$$\int_{-\frac{\pi}{2\omega}}^{\frac{\pi}{2\omega}} \int_{0}^{L} (\dot{y})^2 \, dx \, dt = y_0^{\,2} \; \omega^2 \int_{-\frac{\pi}{2\omega}}^{\frac{\pi}{2\omega}} \cos^3 \omega t \, dt \int_{0}^{L} \sin^2 \frac{\pi x}{L} \, dx$$

$$= \frac{\pi \; y_0^{\,2} \; \omega \; L}{4} \tag{II-8}$$

Then substituting (II-7) and (II-8) into (II-6) yields

$$\overline{C} = \frac{32}{9 \; \pi^2} \; \rho_f \; C_N \; d \; \omega \; y_0 \tag{II-9}$$

This results shows the linearized damping force is a function of the frequency of oscillation and the amplitude.

APPENDIX III

THE BUOY MOTION EQUATIONS

The general form of the buoy motion equations linearized to represent small excursions from a static reference state can be written:

$$[M_{SB}]\ \{\ddot{u}_{SB}\} + [C_{SB}]\ \{\dot{u}_{SB}\} + [K_{SB}]\ \{u_{SB}\} = \{f_{SB}\} \qquad \text{(III-1)}$$

where

$\{u_{SB}\}$, $\{\dot{u}_{SB}\}$, $\{\ddot{u}_{SB}\}$ are the components of the buoy displacement, velocity and acceleration relative to the reference state.

$[M_{SB}]$ is a mass matrix which represents the mass terms for the buoy and the added mass terms for the fluid.

$[C_{SB}]$ is a damping matrix representing the surface wave damping effects.

$[K_{SB}]$ is a restoring force matrix or stiffness matrix.

$\{f_{SB}\}$ represents a set of wave induced excitation forces.

In order to avoid a great deal of complexity, it will be assumed that the buoy is spherical in shape and that a local cartesian coordinate system is selected which is vertical in the z direction and has the incident wave traveling in the +x direction. No loss of generality is incurred with this choice of coordinate system on a spherical buoy since the character of the coefficients do not depend on the orientation or attitude of the buoy. The problem is further simplified if it is assumed that the buoy is homogeneous with the center of gravity at the geometric center of the buoy and that the geometric center is located at the water line in the reference state.

Attachments of hawser and mooring lines to the buoy can be readily handled if their positions relative to the local coordinate system are known. The rigid link transformation of equation (6) in the main text is used for this purpose. The positions of the attachments can be found from the static solution (LIVE LOAD).

Transformation from the local to the global system for assembly of the buoy equations with the rest of the moor system equations is a straightforward process which follows the method outlined in the main text. For this reason only the coefficients in the local coordinate system will be given here. It should be kept in mind that the following equations represent the incremental motion equations for a surface buoy in the local coordinate system just described.

Given that the buoy has a mass designated by m and a mass moment of inertia, J_m, the buoy portion of the mass matrix is

$$[M_B] = \left[\begin{array}{c|c} m\,I_3 & 0 \\ \hline 0 & J_m\,I_3 \end{array}\right] \tag{III-2}$$

Where I_3 is the identity matrix of order 3. The assumption of a homogeneous sphere should be recalled at this point. If the attachments contribute significant mass, their effects can be treated by including additional lumped masses at those nodes.

The added mass has the form:

$$[A] = \begin{bmatrix} A_{xx} & 0 & 0 & 0 & A_{x\theta} & 0 \\ & A_{yy} & 0 & A_{y\phi} & 0 & 0 \\ & & A_{zz} & 0 & 0 & 0 \\ & & & A_{\phi\phi} & 0 & 0 \\ & \text{(SYM)} & & & A_{\theta\theta} & 0 \\ & & & & & A_{\psi\psi} \end{bmatrix} \tag{III-3}$$

The mass matrix is then given by

$$[M_{SB}] = [M_B] + [A] \tag{III-4}$$

The wave damping matrix has a form similar to the added mass matrix. Specific values for the added mass and damping coefficients for a sphere were given by Patton [3]. His values were obtained by curve fitting the analytical results presented by Kim [4]. The nondimensional values obtained were

$$\begin{aligned} M_x &= 1.089 + 0.529\,a' && \text{for } 0 < a' < 0.74 \\ &= 1/(-0.0318 + 0.954\,a') && \text{for } 0.74 < a' < 3.4 \end{aligned} \tag{III-5}$$

$$\begin{aligned} M_z &= 1.85 && \text{for } 0 < a' < 0.1 \\ &= 1.02\,a'^{-0.256} && 0.1 < a' < 3.4 \end{aligned} \tag{III-6}$$

$$\begin{aligned} N_x &= 0 && \text{for } 0 < a' < 0.1 \\ &= -0.069 + 0.715\,a' && \text{for } 0.1 < a' < 1.37 \\ &= 1.595 && \text{for } 1.37 < a' < 3.4 \end{aligned} \tag{III-7}$$

$$\begin{aligned} N_z &= 0.126 + 1.7\,a' && \text{for } 0 < a' < 0.4 \\ &= 1.18\,e^{-0.83a'} && \text{for } 0.4 < a' < 3.4 \end{aligned} \tag{III-8}$$

where a' is the nondimensional frequency given by

$$a' = \frac{2\pi a}{\lambda} = \frac{a\,\omega^2}{g} \tag{III-9}$$

and

a = radius of sphere

λ = wavelength

ω = circular frequency of wave encounter

The added mass terms are nondimensionalized by the factor ρa^3 and the damping terms by the factor $\rho a^3\omega$, thus

$$\begin{aligned} A_{xx} &= A_{yy} = \rho a^3 M_x \\ A_{zz} &= \rho a^3 M_z \end{aligned} \tag{III-10}$$

$$C_{xx} = C_{yy} = \rho a^3 \omega N_x$$
$$C_{zz} = \rho a^3 \omega N_z \qquad \text{(III-11)}$$

The roll, pitch and yaw added mass terms arise from fluid viscosity and they can be written

$$A_{\phi\phi} = A_{\theta\theta} = A_{\psi\psi} = \frac{4\pi \rho a^5}{3} \frac{1 + \beta a}{1 + 2\beta a + 2\beta^2 a^2} \qquad \text{(III-12)}$$

where

$$\beta = \sqrt{\frac{\omega}{2\nu}} \qquad \text{(III-13)}$$

and ν = the kinematic viscosity of the fluid. Since the kinematic viscosity of water is of the order of 10^{-5} ft^2/sec, the rotational added mass terms will be small compared to the buoy inertia terms. Damping due to rotational motion is very small and will be neglected. Thus,

$$C_{\phi\phi} = C_{\theta\theta} = C_{\psi\psi} = 0 \qquad \text{(III-14)}$$

When the center of pressure does not coincide with the center of gravity of the buoy, a coupling between lateral and rotational motions exists. These terms can be written:

$$A_{x\theta} = A_{xx} (z_{cg} - z_{cp})$$
$$A_{y\phi} = -A_{yy} (z_{cg} - z_{cp}) \qquad \text{(III-15)}$$

$$C_{x\theta} = C_{xx} (z_{cg} - z_{cp})$$
$$C_{y\phi} = -C_{yy} (z_{cg} - z_{cp}) \qquad \text{(III-16)}$$

With the origin of the local coordinate system at the geometric center (also center of gravity), z_{cg} is zero. The center of pressure for a half submerged sphere is obtained from

$$z_{cp} = \frac{\int_S z\, n_x\, dS}{\int_S n_x\, dS} = \frac{\int_0^{-a} z \sqrt{a^2 - z^2}\, dz}{\int_0^{-a} \sqrt{a^2 - z^2}\, dz} = \frac{4a}{3\pi} \qquad \text{(III-17)}$$

The damping terms presented above do not represent the effects of viscous drag. The viscous terms involve the square of the relative velocity between the buoy and the fluid and are therefore nonlinear. The viscous effects are generally of less importance than the wave damping. Obviously, this is not the case for the rotational movement since those terms are zero for wave damping. In a free-floating buoy the viscous rotational terms would play an important part, but in a mooring system where the hawser and mooring leg restrain the buoy the rotation is limited. Therefore, all of the viscous terms will be neglected rather than attempting to linearize them.

The only nonzero hydrostatic restoring force on a half-submerged spherical buoy acts in the heave direction. Its value for small displacements is

$$K_{zz} = \pi a^2 \qquad \text{(III-18)}$$

When the buoy provides a connection between a mooring line and a hawser it develops an additional stiffness (resistance to motion) due to the tensile force being transmitted across it. This is analogous to the geometric stiffness term, $[K_G]$, seen in the cable element stiffness matrix in Appendix I. This geometric term has the form

$$[K_B] = [T]^T \frac{P}{L} \left[\begin{array}{c|c} I_3 & -I_3 \\ \hline -I_3 & I_3 \end{array} \right] [T] \qquad \text{(III-19)}$$

where

[T] is the rigid link transformation matrix of equation (6)

$[I_3]$ is the identity matrix of order 3

P is the tension transmitted across the buoy

L is the distance between the attachments

The buoy stiffness is then $[K_B]$ plus the K_{zz} term.

The right-hand side of equation (III-1) represents the forces due to surface waves. Assuming the wave is harmonic in form, Kim [5] shows that the wave induced forces can be written

$$\{f_{SB}\} = \begin{Bmatrix} A^S_{xx}\ \ddot{X}_w + C^S_{xx}\ \dot{X}_w \\ 0 \\ A^S_{zz}\ \ddot{Z}_N + C^S_{zz}\ \dot{Z}_w + I_1\ Z_w \\ 0 \\ A^S_{\Theta\Theta}\ \ddot{\Theta}_w + C^S_{\Theta\Theta}\ \dot{\Theta}_w + I_2\ \Theta_w \\ 0 \end{Bmatrix} \tag{III-20}$$

where

$$A^S_{xx} = \rho a^3\ M^S_x \tag{III-21}$$

$$C^S_{xx} = \rho a^3\ \omega\ N^S_x \tag{III-22}$$

$$I_1 = \rho g \int_S e^{a'(z+ix)}\ n_z\ ds \doteq \rho g \int_S \cos(a'x)\ n_z\ ds \tag{III-23}$$

$$I_2 = \rho g \int_S e^{'(z+ix)}\ (xn_z - zn_x)\ ds \tag{III-24}$$

For the half submerged sphere

$$A^S_{\Theta\Theta}\ C^S_{\Theta\Theta} = I_2 = 0 \tag{III-25}$$

The wave pressure component of the heave exciting force, I_1, is closely approximated by the pressure at the water surface distributed over the cross-section at the water surface. A plot of this function versus the nondimensional frequency is given in Figure III-1.

The values for M_x^S, M_z^S, N_x^S and N_z^S for a half submerged sphere were given by Kim [5]. A polynomial curve fit of those functions plus the curve for I_1 are summarized in the following table:

SUMMARY OF WAVE EXCITING FORCE COEFFICIENTS

FUNCTION	a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7
M_x^S	0.	1.7586	-8.2171	12.0253	-8.2882	3.0081	-0.5575	0.0416
M_z^S	1.7500	-0.8480	-1.9404	3.1652	-2.1289	0.7542	-0.1371	0.0101
N_x^S	1.0833	0.0833	-1.4496	0.7753	-0.0705	-0.0314	0.0055	0
N_z^S	0	8.1558	-24.9364	32.7079	-22.3446	8.2782	-1.5754	0.1206
$I_1/\pi a^2 \rho g$	1.0	-0.0004	-0.1218	-0.0026	0.0069	-0.0007	0.	0.

where the function form is:

$$F = \sum_{i=0}^{N} a_i x^i \qquad \text{(III-26)}$$

Thus all of the terms necessary for treating the small displacement behavior of a restrained, half-submerged spherical buoy are available. The assumptions employed appear to be reasonable and should lead to a good approximation of the buoy effects in a deep sea moor. Although a spherical buoy has been assumed, a comparison of the curves presented by Kim [4] for a sphere and those presented by Garrison [6] for a half-submerged cylindrical buoy with an aspect ratio of 1.0 shows that the added mass and damping coefficients are quite similar. Therefore, it is reasonable to expect the sphere equations to give at least an order-of-magnitude approximation of a cylindrical buoy.

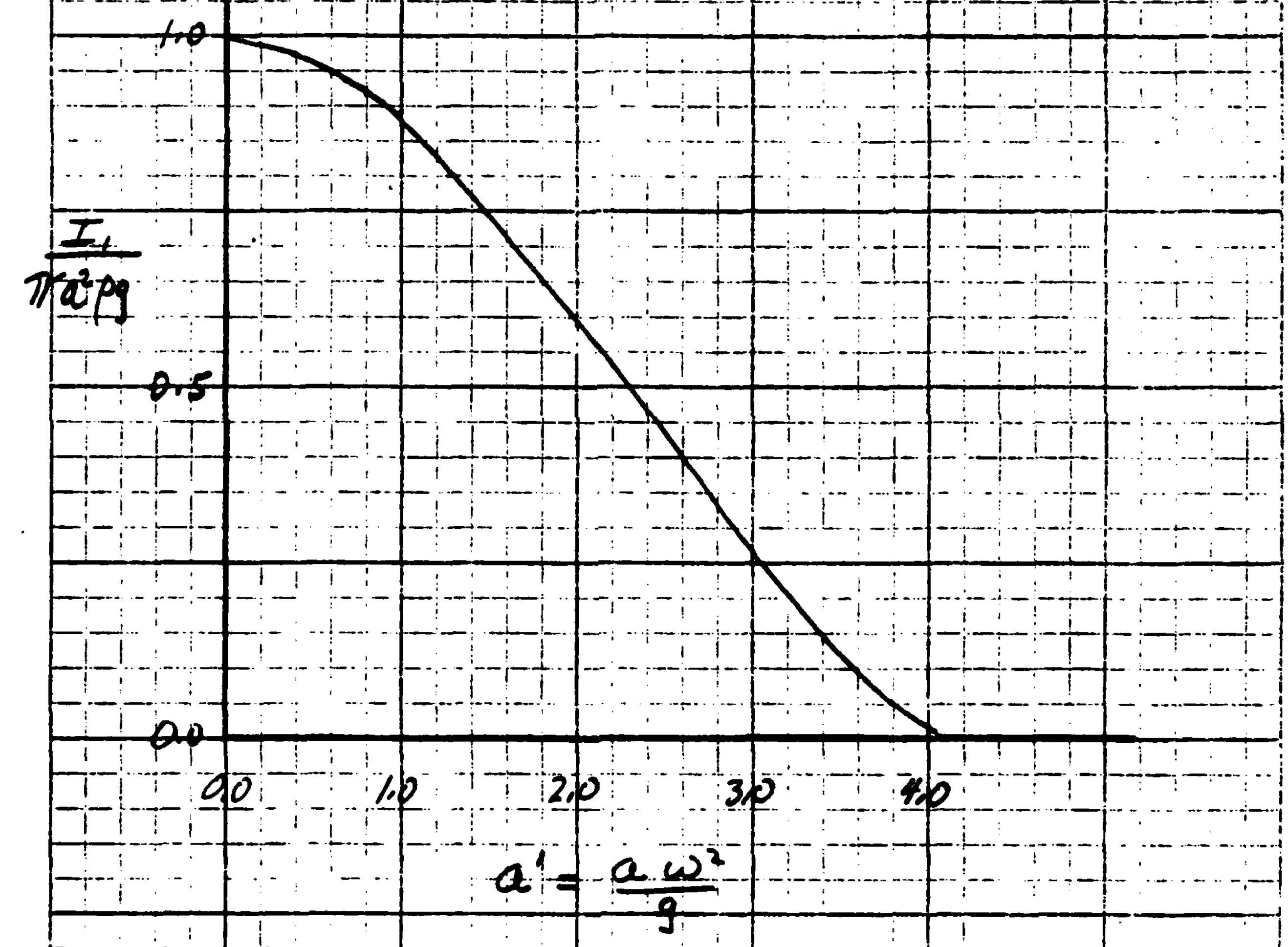


FIG. III-1 HEAVE EXCITING FORCE FOR HALF-SUBMERGED SPHERE

The small displacement assumption deserves some further comment. For wavelengths of the order of the buoy diameter one would expect the buoy motion to be small. However, as the wavelength increases the buoy motions increase. Since most of the wave energy is expected in the longer wavelengths, the buoy could be expected to see large motions which would cause these equations to be inaccurate. When no ship is in the system, this inaccuracy could be serious. Fortunately, the ship motion becomes a significant effect in the longer wavelengths and the buoy motion is dominated by the ship movement as transmitted through the hawser and reacted by the mooring line. In this case the contributions from the buoy itself (though in error) would generally be insignificant. For the shorter wavelengths, the ship appears nearly fixed and the exciting forces due to wave action on the buoy become important. It is fortuitous that this is the range in which the buoy equations are most accurate.

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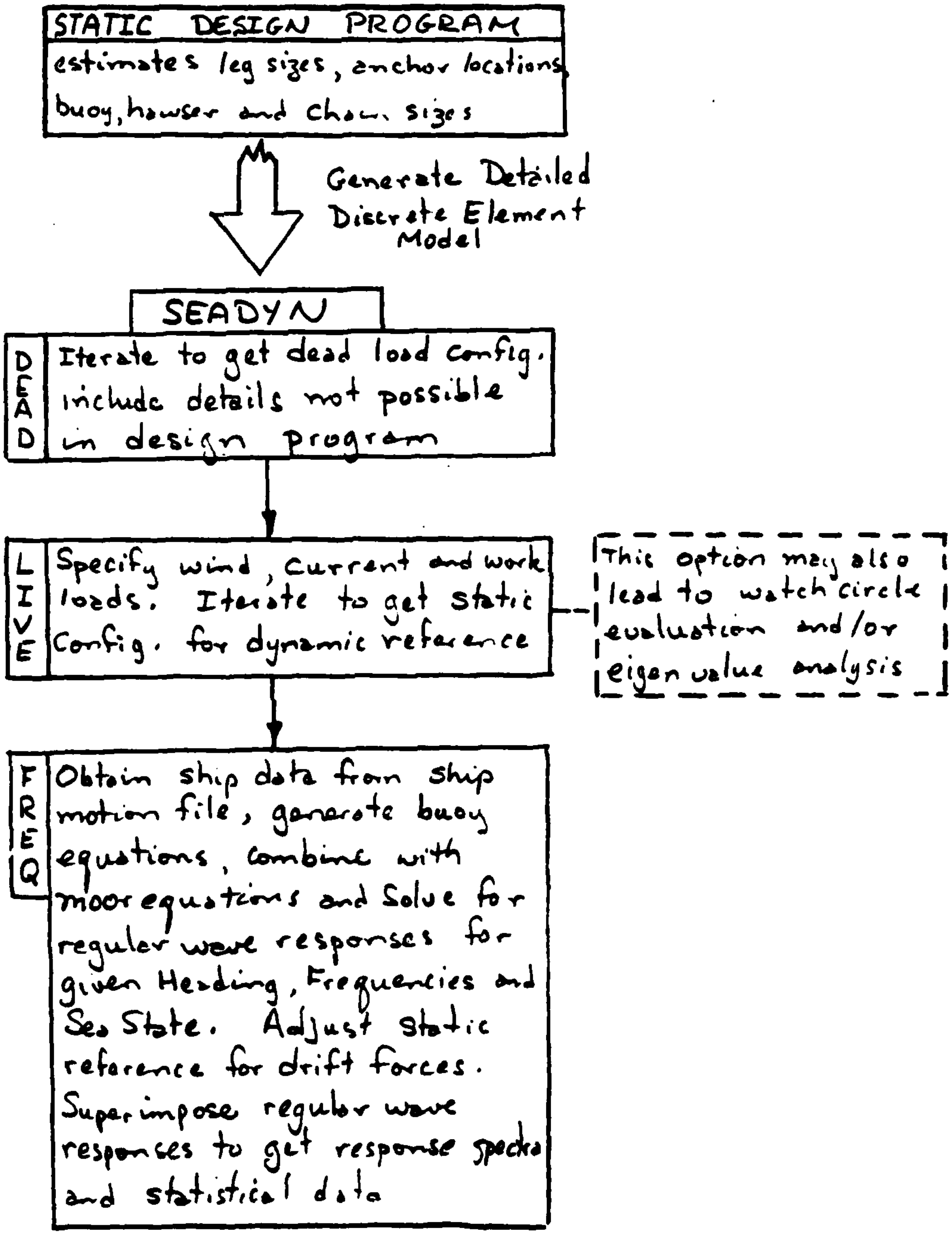

FIGURE 7-1 MACRO-FLOW CHART OF DSSM ANALYSIS WITH SEADYN

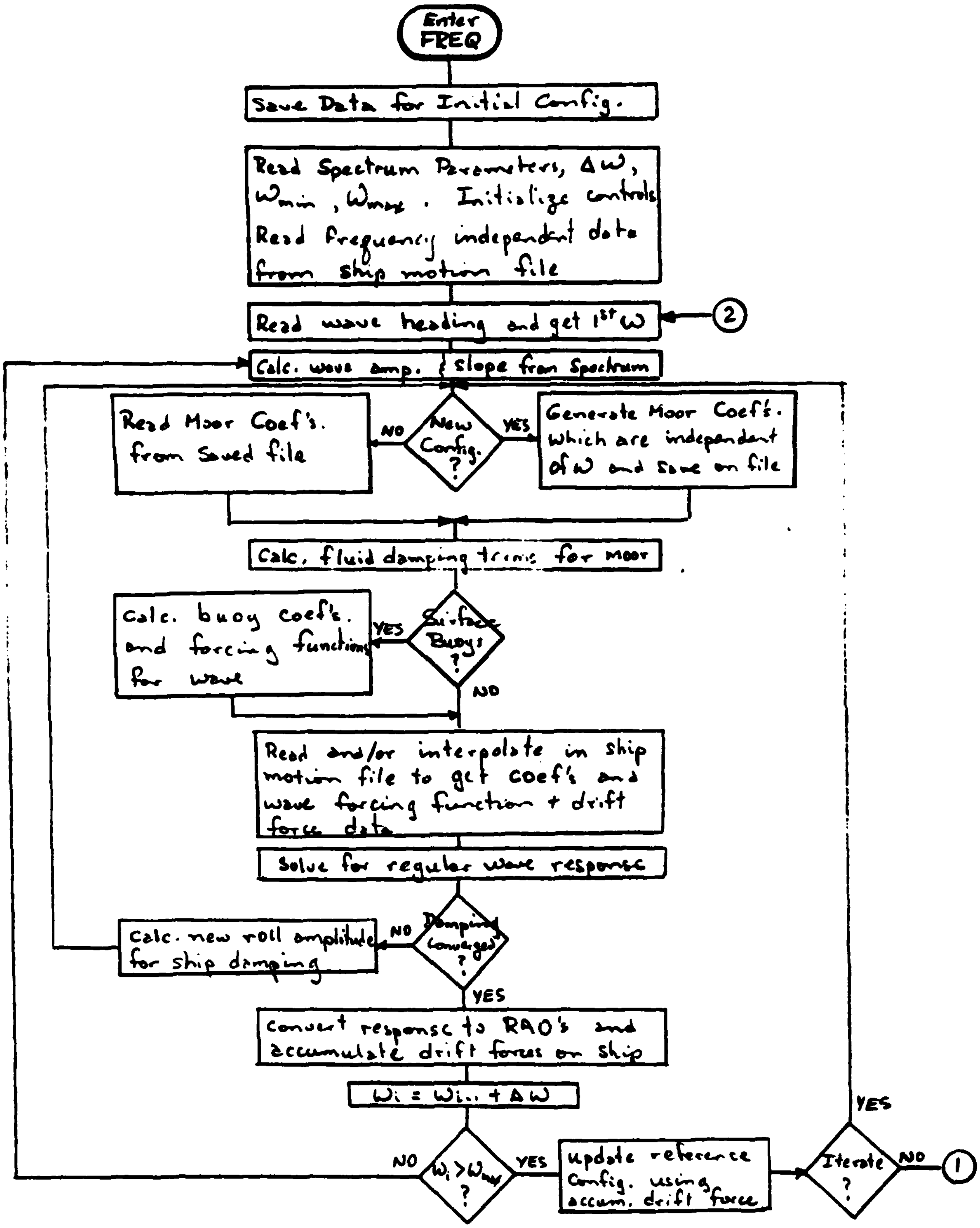

FIGURE 7-2 FLOW CHART OF FREQ SOLUTION OPTION

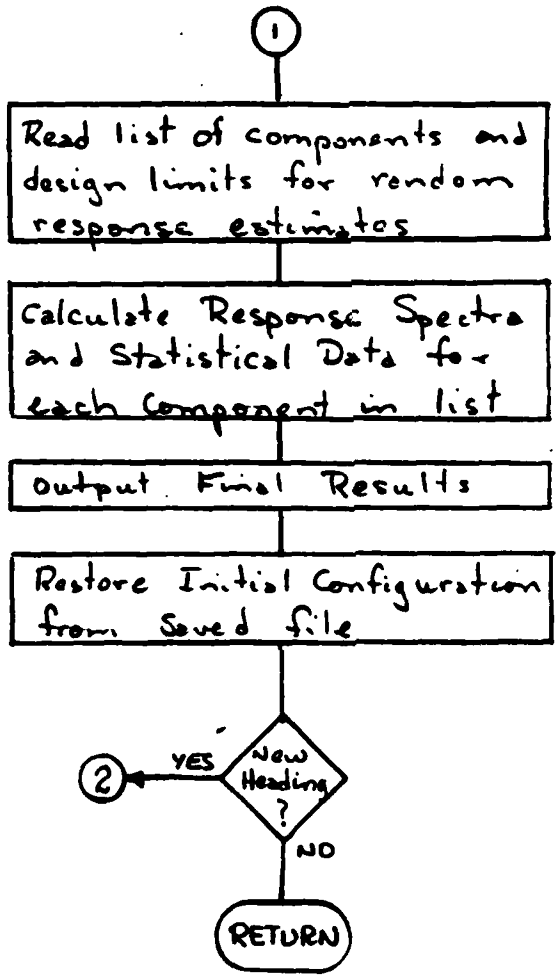

FIGURE 7-2 (CONTINUED) FLOW CHART OF FREQ SOLUTION OPTION

LETTER REPORT NO. 8

INTERIM TECHNICAL REPORT
(Work Package 2, Task 3)

CONTRACT NUMBER N62477-76-C-0002

BY: R.L. Webster

21 September 1976

ELECTRONICS SYSTEMS DIVISION
THE GENERAL ELECTRIC COMPANY
SYRACUSE, NEW YORK 13201

This Letter Report is submitted in compliance with item number (8) of the Milestones and Deliverables Schedule of Contract N62477-76-C-0002, dated 17 June 1975 as revised 4 August 1975.

INTRODUCTION

The purpose of this report is to give an overview of the integrated static and dynamic mooring analysis program for deep sea ship's moors. The procedure for evaluating the acceptability of a moor is presented. In addition, the present status of checkout and validation activities is discussed.

DISCUSSION

The Integrated Program

Full integration of the static and dynamic analysis of a DSSM system has been accomplished within the framework of the SEADYN program. The analytical details were discussed in Letter Report No. 7.

The integrated analysis program begins with a preliminary design of the DSSM and an estimate of the configuration of the ship, its mooring components and working lines (if any). The preliminary design data will generally be obtained with the aid of the static design program developed in Work Package 1 of this effort. The estimate of the starting configuration will usually reflect the state of the system under quiescent conditions (i.e., only gravity/buoyancy acting). The major exception to this is the case of a single point moor which requires some horizontal loading to assure a catenary configuration of the mooring line. The starting configuration is then checked numerically by the program and the configuration adjusted until equilibrium is satisfied.

Upon the specification of the directions and magnitudes of the wind and surface currents, the program will incrementally apply the loading and iteratively check for satisfaction of equilibrium until the static loaded configuration has been attained. This is a fully nonlinear procedure in which the system's geometric nonlinearties, position dependent loading and material nonlinearities are taken into account. It is also possible to specify subsurface currents and various point loads during this stage.

At this point a number of solution options can be employed. These include:

A. Frequency domain dynamic analysis of the effects of surface waves. (See Letter Report No. 7 for details)

B. Eigenvalue analysis to obtain the natural frequencies and modes of vibration neglecting fluid damping effects.

C. Excursion envelope investigations by varying the headings of the wind and surface currents.

D. Evaluation of the adequacy of mooring components.

E. Re-analysis using a different set of static loading conditions.

At the completion of options A, B or D the static solution state is restored. This allows continuation of the calculations by selecting any of the other options. If the adequacy check option is selected following the frequency domain option, then the check is based on the combined effects including wave dynamics rather than just the static state. At the completion of the excursion envelope investigation it is possible to call any of the other options using the final configuration obtained or to return to a previous configuration before proceeding. The user can also save any of the intermediate configurations and restart the analysis at that point on a later run.

A flow chart showing the relationship of these various options of the integrated program is presented in Figure 8-1.

Mooring Validity Assessments

The evaluation of the adequacy of mooring components mentioned in the previous discussion deals with lines, chains, riser buoys, and anchors. The component inventory developed in Work Package 1 is used along with procedures of DM-26 to check for adequacy (see Letter Report No. 5for details). In contrast to the procedures used in the static design program, the procedures used here are validity checks rather than component selections.

The validity check amounts to a table-look-up in the component inventories to find the properties of the component and a comparison of the capability and the loading imposed. A warning message is printed whenever the loading exceeds the capacity. In the event that the component is not listed in the inventory an option is provided to input the capacity at the time the check is requested. Figure 8-2 presents a flow-chart of the procedure.

Program Checkout and Validation Efforts

The source and object files of both the static design program and the integrated SEADYN/DSSM program have been established on the CDC 6700 system at the David Taylor Naval Ship Research and Development Center, Bethesda, MD. Preliminary checkout and demonstration problems have been run on both programs.

These problems have exercised the major options of the static design program including slack and taut moors using the experimental and analytical loading options. Checks against hand calculations have demonstrated the validity of the calculations. Some minor updates of the program files are required and should be completed by 1 October 1976. These updates include an option to alter the units used in the component inventories and to streamline the input for re-design with new constraints.

The SEADYN/DSSM program has been checked out to show that the previous capability of SEADYN remains in tact. The new capability associated with the DSSM effort has been subjected to detailed checkout in all aspects except the surface buoy dynamics equations and the component adequacy checks. Full static and frequency domain analyses have been done on a Mariner class vessel in a four point moor without surface buoys. These test runs have included evaluations of the excursion envelope and the statistical data from the response spectrum. In addition, the steady state responses of an unrestrained ship have been checked against the solution obtained from the DTNSRDC Ship Motion Program. A test case of the NAVFAC construction barge in a four point moor with surface buoys has been exercised through the static analysis. Checkout of the frequency domain analysis with surface buoys is currently underway.

The solution procedures have received close scrutiny. It was found that the introduction of ships and surface buoys in the SEADYN analysis could lead to numerical problems due to matrix ill-conditioning. Special purpose solutions have been written and checked out which attempt to minimize matrix storage space while maintaining a high level of numerical accuracy. These routines have been checked against existing system routines and their accuracy has been established. (It should be noted that the system routines were accurate but were very wasteful of computer storage and therefore were not suitable in SEADYN.) With the checkout

of these new solution routines and some careful modeling of the mooring systems it is possible to reduce the effects of the numerical ill-conditioning and obtain good solutions. It was only after the development of these improvements that successful solutions in both the static analysis and frequency response were obtained.

Checkout of the surface buoy dynamic solutions and the component adequacy checks are now in process. It is anticipated that this checkout and the running of the validation and demonstration problems will be completed by 1 October 1976.

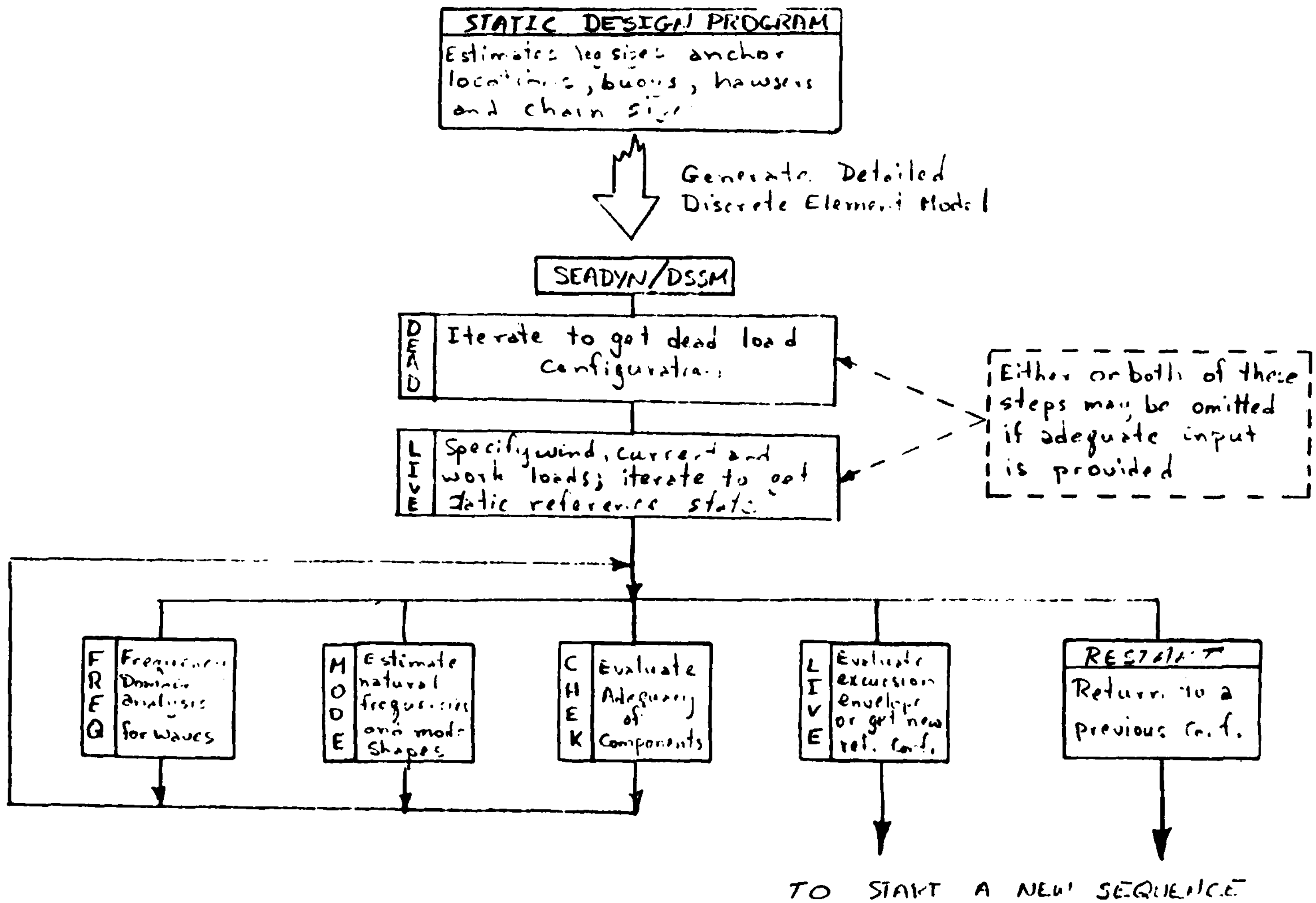

FIGURE 8-1 SEADYN/DSSM ANALYSIS OPTION FLOW CHART

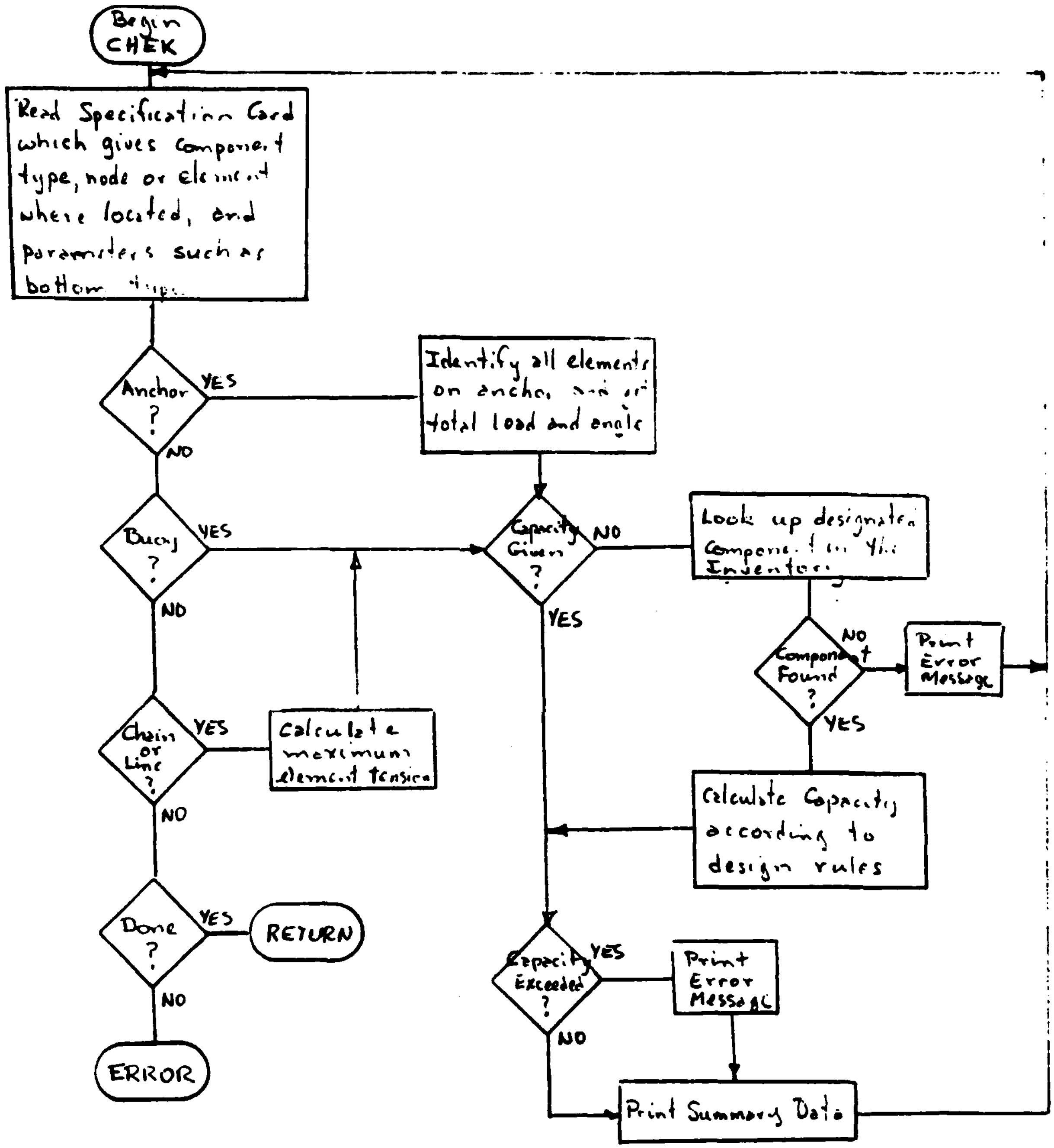

FIGURE 8-2 FLOW CHART OF COMPONENT ADEQUACY CHECK

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LETTER REPORT NO. 9

SUMMARY REPORT OF ACTIVITIES ON WORK PACKAGE 3: SEADYN

CONTRACT NUMBER N62477-76-C-0002

By: R.L. Webster

29 September 1976

ELECTRONICS SYSTEM DIVISION
THE GENERAL ELECTRIC COMPANY
SYRACUSE, NEW YORK 13201

This Letter Report is submitted in compliance with item number (13) of the Milestones and Deliverables Schedule of Contract N62477-76-C-0002, dated 17 June 1975 as revised 4 August 1975. It constitutes the technical report required by that item.

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INTRODUCTION

The digital computer program known as SEADYN is a nonlinear cable/truss/network structural analysis program which was written as part of the doctorial program of Ronald L. Webster at Cornell University. Development of SEADYN was a composite of the author's private efforts and activities associated with various assignments at GE. Documentation of the theoretical background of SEADYN and a brief set of input instructions were included in Dr. Webster's Thesis [1]. However, this did not represent a complete or convenient documentation of the program. The major objective of Work Package 3 was to provide documentation for SEADYN and make it available for use in ocean engineering design and analysis.

In the process of executing work packages 1 and 2 it was determined that much of the capability required for mooring analysis already existed within SEADYN. This led to the decision to fully integrate the DSSM capability into SEADYN rather than duplicate some of its capability in a DSSM program. The obvious advantages to this integration are the reduction of maintenance and a consistent and unified approach to cable and mooring systems. There were other gains due to the fact that some of the features required in the DSSM analysis could be extended to other analyses performed with SEADYN and much of the generality present in SEADYN could be readily transferred to the DSSM effort.

This report briefly describes the status and capabilities of SEADYN prior to the DSSM effort, describes the integration process, and outlines the major changes and improvements in the overall program.

DISCUSSION

Initial Status of SEADYN

The SEADYN program uses the finite element method [2] with displacement unknowns to represent the nonlinear behavior of cable systems. In the fall of 1975 its element library consisted of just one type: a one-dimensional simplex element in three-dimensional space [3]. This element can be used as a truss, a section of a flexible network, or as a portion of a long cable. In addition to this "cable" element, the program had the capability of including lumped bodies at any or all of the nodes in the system. These lumped bodies could be used to represent buoys and anchors. The program was written with fixed dimensions on the arrays which limited it to problems with no more than 30 nodes and 100 elements.

In the development of SEADYN it was assumed that the system could be submerged in a fluid such as sea water and that the imposed loads would include hydrodynamic effects from the relative velocity between an arbitrary flow field and the cable movement. Point loads could also be imposed at any node in the system. Constraints were also provided which could prevent nodes from moving out of the region between the fluid surface and the bottom (the surface and bottom were assumed to be flat and parallel).

One of the distinguishing features of SEADYN is the variety of solution options it provides. These fall within the general categories of incremental or incremental/iterative methods. Working from a Lagrangian viewpoint, the governing equations were developed to include geometric and hyper-elastic material nonlinearities. The solution procedures allow a fixed reference state (total Lagrangian) or an incrementally updated reference (updated Lagrangian). The list of solution options in the fall of 1975 included:

1. Sequence of linear increments (static and dynamic).
2. Residual feedback incremental (static and dynamic).
3. Modified Newton Raphson method (static and dynamic).
4. Time domain dynamic solution using direct numerical integration with a generalized Newmark method.

Static analyses could be done with gravity loading only (dead load) or with currents and/or point loads (live load). Loading in dynamic analyses could be driven by time varying currents and/or point loads or by specified motion of one or more of the nodes. An eigenvalue solution routine was also included for estimating the undamped natural frequencies and mode shapes in any configuration attained by the cable system.

The nonlinear material capability also provided for treatment of slack cable effects so that the snap loading phenomenon could be investigated. A capability for treating time variable cable lengths (payout/reel-in) had been contemplated but not implemented in the program.

SEADYN/DSSM Integration

In the original planning for the DSSM effort it was decided to use SEADYN in both the static analysis and design of the mooring system. This was done because the nonlinearities are significant in the static case and SEADYN had most of the capability required. Subsequently the use of SEADYN in the direct design procedure was found to be too cumbersome and an alternative approach was implemented (see Letter Report No. 4). The need for a static analysis still remained, however. This is because the dynamic analysis procedure requires a static reference state as a beginning point and it was also necessary to modify this reference state as the steady-state wave induced drift forces were estimated. Therefore, it was decided to proceed with modifications of SEADYN to meet the requirements of the DSSM analysis. Specific information on these modifications will be given in the next section.

In the beginning it was not clear whether the dynamic analysis should be incorporated within the SEADYN structure or whether it should merely receive information from SEADYN on the static configuration of the moor. As the details of the dynamic analysis were worked out, it became clear that the dynamic analysis had to be intimately connected to the static analysis in order to deal with the wave drift forces (see Letter Report No. 7). This meant the pertinent portions of SEADYN had to be repeated in the dynamic program or that the dynamic program had to be integrated into SEADYN. The latter was seen to be the more efficient approach.

What has emerged is a much more general capability than had been envisioned in the original work statement. In the first place the integration of SEADYN and the DSSM program removes the need for maintaining two separate programs of considerable complexity and keeping them compatible. More significantly, the sum of the two parts in an integrated form is greater than the sum in a separated form. For example, it is now possible to investigate the behavior of the mooring system through the natural frequencies and mode shapes (a capability not envisioned in the work statement). However, this capability was obtained at no cost since it already existed in SEADYN. On the other hand, the mooring analysis required the ability to deal with rigid bodies (ships) which had multiple connections to them at various spatial positions. The slave/master transformation was developed to meet this need (see next section and Letter Report No. 7) and now that capability is available in SEADYN for modeling other systems such as mooring of large submerged bodies. Also the ability to define external loads through a system of loading functions (ship's static loads) can be used to input loads to bodies other than surface ships, should the need arise. The need to treat hawswer lines in air in addition to the submerged mooring lines has made the ability to treat multiple media systems such as helicopter towed arrays available in SEADYN. Finally, the adequacy checks required in the DSSM work is also available to other SEADYN analysis activities.

Another significant advantage of having an integration of the DSSM capability into SEADYN is in the user/program interface. Now only one user document is required and the user does not have to become familiar with two separate input procedures. Accordingly, all of the documentation requested in Work Package 3 is now included and integrated into the manuals of Work Package 2. It should be emphasized that this does not constitute a reduction of information provided since the entire SEADYN documentation is being provided as requested. The only difference is that it is being packaged within one set of covers instead of two.

Improvements in SEADYN

During the development of the DSSM analysis capability and its integration within SEADYN a number of improvements and additions have been introduced into SEADYN. A partial list of them is provided here. A brief comment is given on

each item. The list contains the major items, but there may be other smaller changes which are not considered significant enough to mention or that have escaped recognition due to the long time span and the many other changes since their introduction. Emphasis is on items which improve or expand the general capability of SEADYN.

1. Variable Dimensional Storage

It was recognized very early that the upper bounds on the number of nodes and elements could be too restrictive. The storage formats for node and element related data were revised to allow dimensions that correspond exactly with the size of the problem being treated. The main program was replaced by a simple routine which allocates the size of COMMON and the calls the subroutine SEADYN. This subroutine reads the problem size input and allocates the storage in the COMMON block. Having completed this, a call is made to the MANIPR subroutine which controls the remaining analysis activities. If any activity requires more storage than is allocated, the analysis is terminated with a message stating the storage required.

2. Slave/Master Transformations

The need for treating non-lumped rigid bodies (ships and mooring buoys) led to the introduction of a rigid link transformation (see Letter Report No. 7 for details). This allows a node to be designated as a slave to another node. It means that the slave node will move as though it is connected to its master node through a rigid arm. This allows the motion of the mooring attachment points to be defined in terms of the movement of the ship or buoy reference point. It is a general capability which can be used for other than ship attachments.

3. Surface Ships

The ability to define a surface ship and its steady-state loading functions was added. The load function descriptions take the same form as those used in the mooring static design program (see Letter Report Nos. 3 and 4). SEADYN allows up to three ships in the system. Although this was not required by the DSSM effort, the work required for this generalization was minor.

4. Mooring Buoys

The buoy input was generalized to model surface buoys with attachments which need not be modeled as lumped at a single point. Steady-state wind and surface current drag effects can be included. SEADYN allows up to 30 buoys to be input.

5. Multiple Media Effects

Two specific gravities can be input (e.g., air, water) and the elements designated as being in one or the other medium. The drag loading, added mass, etc., are altered accordingly. The material property tables also reflect this change. The material weight per unit length is now input and a flag is provided to signal in which fluid it is measured. If a cable material is input with a weight in one medium and the element which uses that material is in the other medium, then the weight values are automatically converted. The program does not treat the movement of a cable element from one medium to another.

6. Improved Solution Routine and Strain Calculations

It was found that ill-conditioning of the matrix equations became a problem with the introduction of ships and mooring buoys. In addition iterative solutions tended to give erratic results. A close review of the banded simultaneous solution routine turned up an error and numerical inaccuracies. This routine was rewritten and double precision accumulations of products was included. The result was an improvement in iterative solution convergence and error propagation. Introduction of double precision calculations of element length changes also improved convergence characteristics of iterative solutions.

7. Generalized Control of Modified Newton-Raphson Solutions

Additional control of the iterations and acceleration schemes in the modified Newton-Raphson routine have been provided. These allow for more user control of various features of the solution method.

8. Addition of a Frequency Domain Solution

This is the primary solution block for the DSSM dynamic calculations, but under some conditions it can be used to calculate linearized dynamic responses of other systems (e.g., moored buoy with no ship in the system, non-slender platforms for which coefficients are provided). The basic capability opens the door for further generalizations and improvements.

9. Validity/Adequacy Checks

The program can use the component inventory developed in Work Package 1 (see Letter Report No. 5) or input values for component capacities which can be used to evaluate the validity or adequacy of the system under various load states. This check can be made regardless of the system being analyzed.

10. New Input Generation Schemes

A scheme to generate nodes and obtain element tension estimates along a predetermined catenary has been added. This facilitates the input of a stable initial configuration based on output from the static design program.

11. Generalized LIVE Option

The LIVE option in SEADYN has been generalized to allow sequential variations in the directions of the surface wind and current. This facilitates the investigation of mooring excursion limits.

12. Generalized DYN Option

The iterative time domain solution in the DYN option has been generalized to include the three parameter generalized Newmark difference equations [1]. The effort required was minimal and was included in the original planning for Work Package 3.

13. Generalized Point Load Variations

The point load input for static loading has been generalized to allow specifications of loads that increase, decrease or do not change with the load increment. This should aid in getting reference states for certain difficult configurations.

It should be noted that, besides the surface ship and mooring buoys, no additional elements have been added to SEADYN. The cable element is still the one-dimensional simplex element. The program still maintains its modular structure and the element library could be expanded with little impact to the overall program structure. Other elements which may be of interest are higher order cable elements and/or flexure elements. Since there was no provision in Work Package 3 for significant expansion of the SEADYN capability beyond that required to meet the DSSM objectives, neither these improvements nor the addition of pay-out/ reel-in capability were included in this effort.

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ADDENDUM I

DEBUG AND VERIFICATION ACTIVITIES DURING 1977 AND 1978
(May 1978)

With the initial submittal of the contract deliverables, it was apparent that the results obtained on the demonstration cases involving mooring buoys and hawsers (cases 1-3 and 5) were unreasonable. The dynamic tensions in the hawsers were the most obvious signal of problems. The original submittal of the seven demonstration cases was made on 22 November 1976. A review of these results led to an identification and correction of an error in the random response calculations and the ship motion file. Subsequent evaluations led to a correction of an error in the static loads on the ship. A rerun of the demonstration case on 4 December 1976 represented the final runs of the initial submittal of the deliverables. These results were given careful scrutiny and it was concluded that there was an error or errors involving the mooring buoys. This prompted a thorough review of the entire SEADYN/DSSM with special emphasis on the buoy subroutine. This effort was begun in April of 1977 and in May a major coding error was found in the buoy dynamics subroutine. As the review continued, an error was also found in the linearized damping subroutine. A rerun of demonstration case 2 in May showed only marginal improvement in the results. It was still obvious that the hawser tensions were far too large. The buoy equations were again reviewed and the program was extended to allow frequency domain calculations without ships (buoys and lines only). During studies with a single buoy and mooring leg, it was found that the GE and the DTNSRDC versions of the program did not get the same answers. Although it was possible to show that the DTNSRDC file was wrong, attempts to find the error were fruitless and in June 1977, the DTNSRDC file was regenerated from the GE deck.

The summer of 1977 was spent in a low level effort to completely review the SEADYN/DSSM program. This effort produced some minor corrections which had little or no effect on the buoy dynamics. During this period, improvements

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in the MNR solution method were introduced. The most noticeable change was the introduction of yaw motion convergence checks on the static solutions involving ships. This led to marked improvements in the solution convergence rate and solution cost. However, applying the same scheme to the angular position of mooring buoys proved to be totally ineffective and caused an order of magnitude increase in solution cost. The procedure was therefore kept on the ship's yaw term but abandoned on the buoy angular term. Another improvement in the MNR solution that was introduced in this period was an extrapolation procedure which attempts to recover from an overshoot of the surface or bottom constraint. Also introduced was a generalization of constraints introduced when an anchor encounters a bottom limit. It was found in ship excursion calculations with SEADYN/DSSM that fixing all motion components as the anchor meets the bottom produces an artificial history or path dependence. Thus an option was added to allow the constraint to be on all components or only the vertical one. Fixing only the vertical component removes the path dependence. The overall result of these improvements was the desensitizing of the static solutions and the improvement of convergence characteristics.

Late in August of 1977, a major improvement in the solution accuracy of the mooring buoy demonstration cases was obtained. It was accomplished simply by noting the presence of an input error in the buoy properties. Back in the initial program development when considerable problems were being encountered with static solutions, the buoyancy in the test cases was input artificially high to avoid some surface interaction problems. After the static solution problems had been solved, the artificial buoyancy was forgotton and left on the card during the dynamic test runs. This high buoyancy led to an erroneous calculation of a very high mass for the mooring buoys in case 1-3. Correction of this input error produced the first reasonable results for case 2. A complete evaluation of buoy and ship motions were then undertaken. During these efforts, the effects of the initial buoy attitude were evaluated by comparing the dynamic results with the buoys locked in an attitude representative of the static reference state. These comparisons showed

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the differences were minor. From early September 1977 through November, the results from case 2 were thoroughly reviewed and tested, and it was finally concluded that the results were reasonable. At this point, the input of all of the other demonstration cases were reviewed in preparation for final reruns.

Early in 1978, yet another error was found in the static loads on ships. This was detected when the final updates were being made to bring the ship loads in DESMOOR in correspondence with SEADYN/DSSM. This error occurred when water depth scaling was necessary on a ship with a propeller with loads defined from a table. This error was most apparent on head and follower loads. Since only one of the demonstration cases (case 5) had head loading and the SEACON barge had no propeller, this error had minor influence on the demonstration case results.

Final rerun of the seven demonstration cases was completed in March 1978. The time domain correlation runs were then undertaken and completed in early May. The results of these efforts are discussed in the Acceptance Report. As a closing effort, all of the documents were reviewed and updated. Major revisions were made in the User's Manuals for DESMOOR [8]* and SEADYN/DSSM [5], and the Acceptance Report [9]. This addendum was then made to the Final Report.

*Bibliography found on page 36.

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